



## LINEAR EXPANSION OF MISCELLANEOUS SUBSTANCES.

The coefficient of cubical expansion may be taken as three times the linear coefficient.  $t$  is the temperature or range of temperature,  $C$  the coefficient of expansion, and  $A$ . the authority.

Substance.	$t$	$C \times 10^4$	A.	Substance.	$t$	$C \times 10^4$	A.
Brass:				Platinum-silver:			
Cast.....	0-100	0.1875	1	1 Pt + 2 Ag.....	0-100	0.1523	4
Wire.....	"	0.1930	1	Porcelain.....	20-790	0.0413	19
	"	.1783-.193	2	" Bayeux.....	1000-1400	0.0553	20
71.5 Cu + 27.7 Zn +				Quartz:			
0.3 Sn + 0.5 Pb...	40	0.1859	3	Parallel to axis...	0-80	0.0797	6
71 Cu + 29 Zn.....	0-100	0.1906	4	" ".....	-190 to + 16	0.0521	21
Bronze:				Perpend. to axis...	0-80	0.1337	6
3 Cu + 1 Sn.....	16.6-100	0.1844	5	Quartz glass.....	-190 to + 16	-0.0026	13
" " " ".....	16.6-350	0.2116	5	" ".....	16 to 500	0.0057	26
" " " ".....	16.6-957	0.1737	5	" ".....	16-1000	0.0058	26
86.3 Cu + 9.7 Sn +				Rock salt.....	40	0.4040	3
4 Zn.....	40	0.1782	3	Rubber, hard.....	0	0.691	27
97.6 Cu +	0-80	0.1713	6	" ".....	-160	0.300	27
2.2 Sn + { hard		0.1708	6	Speculum metal...	0-100	0.1933	1
0.2 P { soft				Topaz:			
Caoutchouc.....	—	0.657-0.686	2	Parallel to lesser			
	16.7-25.3	0.770	7	horizontal axis...	"	0.0832	8
Constantan.....	4-29	0.1523	—	Parallel to greater	"	0.0836	8
Ebonite.....	25.3-35.4	0.842	7	horizontal axis...	"	0.0472	8
Fluor spar: CaF <sub>2</sub> ...	0-100	0.1950	8	Parallel to vertical	"		
German silver.....	"	0.1836	8	axis.....	"	0.0773	8
Gold-platinum:				Tourmaline:			
2 Au + 1 Pt.....	"	0.1523	4	Parallel to longi-		0.0937	8
Gold-copper:				tudinal axis....			
2 Au + 1 Cu.....	"	0.1552	4	Parallel to horizon-		0.0773	8
Glass:				tal axis.....	16.6-254	0.1952	5
Tube.....	"	0.0833	1	Type metal.....	0-18	0.6360	22
" ".....	"	0.0828	9	Vulcanite.....	0-100	0.0890	5
Plate.....	"	0.0801	10	Wood:			
Crown (mean).....	"	0.0807	10	Parallel to fiber:			
Flint.....	50-60	0.0954	11	Ash.....	"	0.0951	23
Jena ther-16 <sup>III</sup> }	0-100	0.081	12	Beech.....	2.34	0.0257	24
monometer   normal				Chestnut.....	"	0.0649	24
" " 59 <sup>III</sup> .....	"	0.058	12	Elm.....	"	0.0565	24
" ".....	-191 to + 16	0.424	13	Mahogany.....	"	0.0361	24
Gutta percha.....	20	1.083	14	Maple.....	"	0.0638	24
Ice.....	-20 to -1	0.51	15	Oak.....	"	0.0492	24
Iceland spar:				Pine.....	"	0.0541	24
Parallel to axis....	0-80	0.2631	6	Walnut.....	"	0.0658	24
Perpendicular to axis	"	0.0544	6	Across the fiber:			
Lead-tin (solder)				Beech.....	"	0.614	24
2 Pb + 1 Sn.....	0-100	0.2508	1	Chestnut.....	"	0.325	24
Magnalium.....	12-39	0.238	16	Elm.....	"	0.443	24
Manganin.....	—	0.181	—	Mahogany.....	"	0.404	24
Marble.....	15-100	0.117	17	Maple.....	"	0.484	24
Paraffin.....	0-16	1.0662	18	Oak.....	"	0.544	24
" ".....	16-38	1.3030	18	Pine.....	"	0.341	24
" ".....	38-49	4.7707	18	Walnut.....	"	0.484	24
Platinum-iridium				Wax: White.....	10-26	2.300	25
10 Pt + 1 Ir.....	40	0.0884	3	" ".....	26-31	3.120	25
				" ".....	31-43	4.860	25
				" ".....	43-57	15.227	25
References:							
(1) Smeaton.	(8) Pfaff.	(15) Mean.	(22) Mayer.				
(2) Various.	(9) Deluc.	(16) Stadhagen.	(23) Glatzel.				
(3) Fizeau.	(10) Lavoisier and Laplace.	(17) Fröhlich.	(24) Villari.				
(4) Matthiessen.	(11) Pulfrich.	(18) Rodwell.	(25) Kopp.				
(5) Daniell.	(12) Schott.	(19) Braun.	(26) Randall.				
(6) Benoit.	(13) Henning.	(20) Deville and Troost.	(27) Dorsey.				
(7) Kohlrausch.	(14) Russner.	(21) Scheel.					

TABLE 241.

## CUBICAL EXPANSION OF LIQUIDS.

If  $V_0$  is the volume at  $0^\circ$  then at  $t^\circ$  the expansion formula is  $V_t = V_0 (1 + \alpha t + \beta t^2 + \gamma t^3)$ . The table gives values of  $\alpha$ ,  $\beta$  and  $\gamma$  and of  $C$ , the true coefficient of cubical expansion, at  $20^\circ$  for some liquids and solutions.  $\Delta t$  is the temperature range of the observation and  $A$  the authority.

Liquid.	$\Delta t$	$\alpha \times 10^3$	$\beta \times 10^6$	$\gamma \times 10^8$	$C \times 10^3$ at $20^\circ$	$A$
Acetic acid	16-107	1.0630	0.12636	1.0876	1.071	3
Acetone	0-54	1.3240	3.8090	-0.87983	1.487	3
Alcohol:						
Amyl	-15-80	0.9001	0.6573	1.18458	0.902	4a
Ethyl, 30% by vol.	18-39	0.2928	10.790	-11.87	-	6
" 50% "	0-39	0.7450	1.85	0.730	-	6
" 99.3% "	27-46	1.012	2.20	-	1.12	6
" 500 atmo. press.	0-40	0.866	-	-	-	1
" 3000 " "	0-40	0.524	-	-	-	1
Methyl	0-61	1.1342	1.3635	0.8741	1.199	5a
Benzene	11-81	1.17626	1.27776	0.80648	1.237	5a
Bromine	0-59	1.06218	1.87714	-0.30854	1.132	2
Calcium chloride:						
5.8% solution	18-25	0.07878	4.2742	-	0.250	7
40.9% "	17-24	0.42383	0.8571	-	0.458	7
Carbon disulphide	-34-60	1.13980	1.37065	1.91225	1.218	4a
500 atmo. pressure	0-50	0.940	-	-	-	1
3000 " "	0-50	0.581	-	-	-	1
Carbon tetrachloride	0-76	1.18384	0.89881	1.35135	1.236	4b
Chloroform	0-63	1.10715	4.66473	-1.74328	1.273	4b
Ether	-15-38	1.51324	2.35918	4.00512	1.656	4a
Glycerine	-	0.4853	0.4895	-	0.505	8
Hydrochloric acid:						
33.2% solution	0-33	0.4460	0.215	-	0.455	9
Mercury	0-100	0.18182	0.0078	-	0.18186	13
Olive oil	-	0.6821	1.1405	-0.539	0.721	10
Pentane	0-33	1.4646	3.09319	1.6084	1.608	14
Potassium chloride:						
24.3% solution	16-25	0.2695	2.080	-	0.353	7
Phenol	36-157	0.8340	0.10732	0.4446	1.090	11
Petroleum:						
Density 0.8467	24-120	0.8994	1.396	-	0.955	12
Sodium chloride:						
20.6% solution	0-29	0.3640	1.237	-	0.414	9
Sodium sulphate:						
24% solution	11-40	0.3599	1.258	-	0.410	9
Sulphuric acid:						
10.9% solution	0-30	0.2835	2.580	-	0.387	9
100.0% "	0-30	0.5758	-0.432	-	0.558	9
Turpentine	-9-106	0.9003	1.9595	-0.44998	0.973	5b
Water	0-33	-0.06427	8.5053	-6.7900	0.207	13

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## COEFFICIENTS OF THERMAL EXPANSION.

## Coefficients of Expansion of Gases.

Pressures are given in centimeters of mercury.

Coefficient at Constant Volume.				Coefficient at Constant Pressure.			
Substance.	Pressure cm.	Coeffi- cient × 100.	Reference.	Substance.	Pressure cm.	Coeffi- cient × 100.	Reference.
Air . . . . .	.6	.37000	1	Air . . . . .	76.	.3671	3
" . . . . .	1.3	.37172	"	" . . . . .	257.	.3693	"
" . . . . .	10.0	.36930	"	" 0°-100° . . . . .	100.1	.36728	2
" . . . . .	25.4	.36580	"	Hydrogen 0°-100° . . . . .	100.0	.36000	"
" . . . . .	75.2	.36060	"	" . . . . .	200 Atm.	.332	9
" 0°-100° . . . . .	100.1	.36744	2	" . . . . .	400 "	.295	"
" . . . . .	76.0	.36050	3	" . . . . .	600 "	.261	"
" . . . . .	200.0	.36003	"	" . . . . .	800 "	.242	"
" . . . . .	2000.	.38866	"	Carbon dioxide . . . . .	76.	.3710	3
" . . . . .	10000.	.4100	"	" " 0°-20° . . . . .	51.8	.37128	2
Argon . . . . .	51.7	.3608	4	" " 0°-40° . . . . .	51.8	.37100	"
Carbon dioxide . . . . .	76.0	.36856	3	" " 0°-100° . . . . .	51.8	.37073	"
" " . . . . .	1.8	.36753	1	" " 0°-20° . . . . .	99.8	.37002	"
" " . . . . .	5.6	.36641	"	" " 0°-100° . . . . .	99.8	.37410	"
" " . . . . .	74.0	.37264	"	" " 0° 20° . . . . .	137.7	.37972	"
" " 0°-20° . . . . .	51.8	.36985	2	" " 0°-100° . . . . .	137.7	.37703	"
" " 0°-40° . . . . .	51.8	.36972	"	" " 0° 7.5° . . . . .	2021.	.1007	6
" " 0°-100° . . . . .	51.8	.36981	"	" " 64° 100° . . . . .	26.1.	.6574	"
" " 0°-20° . . . . .	99.8	.37335	"	Carbon monoxide . . . . .	76.	.3666	3
" " 0°-100° . . . . .	99.8	.37262	"	Nitrous oxide . . . . .	76.	.3710	"
" " 0°-100° . . . . .	100.0	.37248	5	Sulphur dioxide . . . . .	76.	.3903	"
Carbon monoxide . . . . .	76.	.36667	3	" . . . . .	98.	.3980	"
Helium . . . . .	56.7	.3665	4	Water- vapour { 0° 110° . . . . .	76.	.4187	10
Hydrogen 16°-132° . . . . .	.0077	.3328	6	{ 0° 141° . . . . .	76.	.4180	"
" " 15°-132° . . . . .	.025	.3623	"	{ 0°-162° . . . . .	76.	.4071	"
" " 12°-185° . . . . .	.47	.3956	"	{ 0°-206° . . . . .	76.	.3938	"
" . . . . .	.93	.37002	1	{ 0°-247° . . . . .	76.	.3799	"
" . . . . .	11.2	.36548	"				
" . . . . .	76.4	.36501	"				
" " 0°-100° . . . . .	100.0	.36626	2				
Nitrogen 13°-132° . . . . .	.06	.3621	6				
" " 9°-133° . . . . .	.53	.3290	"				
" " 0°-20° . . . . .	100.2	.36754	2				
" " 0°-100° . . . . .	100.2	.36744	"				
" . . . . .	76.	.36682	7				
Oxygen 11°-132° . . . . .	.007	.4161	6				
" " 9°-132° . . . . .	.25	.3684	"				
" " 11°-132° . . . . .	.51	.3831	"				
" . . . . .	1.0	.36683	8				
" . . . . .	18.5	.36000	"				
" . . . . .	75.9	.36681	"				
Nitrous oxide . . . . .	76.	.3676	3				
Sulphur dioxide SO <sub>2</sub> . . . . .	76.	.3845	"				

Thomson has given, *Encyc. Brit.* "Heat," the following for the calculation of the expansion,  $E$ , between 0° and 100° C. Expansion is to be taken as the change of volume under constant pressure:

Hydrogen, $E$	.3662(1 - .00040 $I/v$ ),
Air, $E$	.3662(1 - .0026 $I/v$ ),
Oxygen, $E$	.3662(1 - .0032 $I/v$ ),
Nitrogen, $E$	.3662(1 - .0031 $I/v$ ),
CO <sub>2</sub> , $E$	.3662(1 - .0161 $I/v$ ).

$I/v$  is the ratio of the actual density of the gas at 0° C. to what it would have at 0° C. and 1 Atm. pressure.

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- 3 Regnault, Ann. chim. phys. (3) 5, 1842.
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- 7 Andrews, Proc. Roy. Soc. 24, 1876.
- 8 Meleander, Acta Soc. Fenn. 10, 1891.
- 9 Amagat, C. R. 111, 1890.
- 10 Hün, Théorie méc. chaleur, 1862.

TABLE 243.

## SPECIFIC HEAT OF THE CHEMICAL ELEMENTS.

Element.	Range* of temperature, C	Specific heat.	Reference.	Element.	Range* of temperature, C	Specific heat.	Reference.
Aluminum.....	-240.6	.0092	45	Cobalt.....	500	.1452	18
".....	-190.0	.0889	45	".....	1000	.204	18
".....	-73.0	.190	46	".....	-182 to +15	.0822	19
".....	-190 to -82	.1466	47	".....	15-100	.1030	19
".....	-76 to -1	.1962	47	Copper j.....	-249.5	.0035	45
".....	+16 to +100	.2122	48	".....	-223	.0208	46
".....	+16 to +304	.2250	48	".....	-185	.0532	45
".....	-250	.1428	1	".....	-63	.0865	46
".....	0	.2080	1	".....	+25	.0917	44
".....	100	.2226	1	".....	76	.0937	51
".....	250	.2382	1	".....	84	.0938	51
".....	500	.2739	1	".....	100	.0942	2
".....	16-100	.2122	43	".....	362	.0997	51
Antimony.....	15	.0489	2	".....	900	.1250	20
".....	100	.0503	2	".....	15-238	.0951	43
".....	200	.0520	2	".....	-181 to 13	.0868	21
Arsenic, gray.....	0-100	.0822	3	".....	23-100	.0940	21
Arsenic, black.....	0-100	.0861	3	Gallium, liquid.....	12 to 113	.080	22
Barium.....	-185 to +20	.068	4	" solid.....	12-23	.079	22
Bismuth.....	-186	.0284	5	Germanium.....	0-100	.0737	23
".....	0	.0301	6	".....	-185 to +20	.033	4
".....	75	.0309	6	".....	0-100	.0316	24
".....	20-100	.0302	7	Indium.....	0-100	.0570	13
" fluid.....	280-380	.0303	8	Iodine.....	-90 to +17	.0485	49
Boron.....	0-100	.307	9	".....	-191 to -80	.0454	49
".....	-191 to -78	.0707	47	".....	0-98	.0541	25
".....	-76 to 0	.1677	47	Iridium.....	-186 to +18	.0282	20
Bromine, solid.....	-78 to -20	.0843	10	".....	18-100	.0323	26
" solid.....	-192 to -80	.0702	49	Iron.....	-223	.0776	46
" fluid.....	13-45	.107	11	".....	-163	.0622	46
Cadmium.....	-223	.0308	46	".....	-63	.0961	46
".....	-173	.0478	46	".....	+37	.1092	46
".....	-73	.0533	46	" cast.....	20-100	.1180	27
".....	21	.0551	2	" wrought.....	15-100	.1152	28
".....	100	.0570	2	" wrought.....	1000-1200	.1980	28
".....	200	.0594	2	" wrought.....	500	.176	28
".....	300	.0617	2	" hard-drawn.....	0-18	.0986	29
Cesium.....	0-26	.0482	12	" hard-drawn.....	20-100	.1146	29
Calcium.....	-185 to +20	.157	4	".....	-185 to +20	.0958	4
".....	0-181	.170	13	".....	0 to +200	.1175	53
Carbon, graphite.....	-191 to -79	.0573	47	".....	0 to +300	.1233	53
".....	-76 to 0	.1255	47	".....	0 to +400	.1282	53
".....	50	.114	14	".....	0 to +500	.1338	53
".....	+11	.160	14	".....	0 to +600	.1396	53
".....	977	.467	14	".....	0 to +700	.1487	53
".....	1730	.50	52	".....	0 to +800	.1597	53
" Acheson.....	-244	.005	50	".....	0 to +900	.1644	53
".....	-186	.027	50	".....	0 to +1000	.1557	53
Carbon, diamond.....	50	.0635	47	".....	0 to +1100	.1534	53
".....	+11	.113	47	Lanthanum.....	0-100	.0448	15
".....	985	.459	47	Lead.....	-250	.0143	40
Cerium.....	0-100	.0448	15	".....	-236	.0217	46
Chlorine, liquid.....	0-24	.2262	16	".....	-193	.0276	46
Chromium.....	-200	.0666	17	".....	-73	.0295	46
".....	0	.1039	17	".....	15	.0299	2
".....	100	.1121	17	".....	100	.0311	2
".....	600	.1872	17	".....	300	.0338	2
".....	-185 to +20	.086	4	" fluid.....	310	.0356	30

\* When one temperature is given, the "true" specific heat is indicated, otherwise the "mean" specific heat.

†  $0.3834 + 0.00020(t - 25)$  intern. j per g degree =  $0.0917 + 0.000048(t - 25)$  cal/g per g degree. (Griffith, 1913.)

## SPECIFIC HEAT OF THE CHEMICAL ELEMENTS.

Element.	Range * of temperature, °C	Specific heat.	Refer-ence.	Element.	Range * of temperature, °C	Specific heat.
Lead.....	00	0.0312	51	Potassium.....	-191 to -80	0.1868
".....	210	0.0334	51	".....	-78 to 0	0.1000
".....	18-100	0.0310	43	".....	-183 to +20	0.1200
".....	10-250	0.0319	43	Rhodium.....	0 97	0.0580
Lithium.....	-191 to -80	0.521	47	Rubidium.....	0 100	0.0800
".....	-78 to 0	0.505	47	Ruthenium.....	0 100	0.0610
".....	-75 to +19	0.620	47	Selenium.....	-188 to +18	0.068
".....	-100	0.5997	31	Silicon.....	-185 to +20	0.124
".....	0	0.7951	31	".....	39 8	0.1360
".....	50	0.9063	31	".....	+57.1	0.183
".....	100	1.0107	31	".....	212	0.2020
".....	190	1.3745	31	Silver.....	-238	0.0131
Magnesium.....	-185 to +20	0.222	4	".....	-213	0.0307
".....	00	0.2492	7	".....	173	0.0447
".....	325	0.3235	7	".....	-73	0.0510
".....	625	0.4352	7	".....	127	0.0560
".....	20-100	0.2492	7	".....	0 100	0.0550
Manganese.....	-183 to -79	0.6820	49	".....	24	0.0546
".....	-79 to +15	0.1001	49	".....	100	0.0560
".....	0	0.1211	49	".....	500	0.0581
".....	325	0.1783	49	".....	17507	0.0508
".....	20-100	0.1211	49	".....	800	0.076
".....	-100	0.0079	31	" fluid.....	697 1100	0.0748
".....	0	0.1072	31	Sodium.....	185 to +20	0.253
".....	100	0.1143	31	".....	-191 to -83	0.233
Mercury, sol.....	-77 to -42	0.0320	47	".....	77 to 0	0.270
" liq.....	-30 to -3	0.0341	47	".....	-224	0.182
".....	-185 to +20	0.032	3	".....	184	0.210
".....	0	0.03440	32	Sulphur.....	-188 to +18	0.147
".....	85	0.0328	32	" rhombic.....	0 54	0.1728
".....	100	0.03284	2	" monoclin.....	0 52	0.1800
".....	250	0.03212	2	" liquid.....	119 147	0.235
Molybdenum.....	-185 to +20	0.062	4	Tantalum.....	-185 to +20	0.033
".....	60	0.0647	7	".....	1400	0.013
".....	475	0.0750	7	Tellurium.....	-183 to +18	0.047
".....	20 to 100	0.0647	7	" crys.....	15 100	0.038
Nickel.....	-185 to +20	0.092	4	Thallium.....	-185 to +20	0.048
".....	100	0.1128	18	".....	20 100	0.0426
".....	300	0.1403	18	Thorium.....	0 100	0.0276
".....	500	0.1290	18	Tin.....	196 to -79	0.0380
".....	1000	0.1608	18	".....	76 to +18	0.0518
".....	18-100	0.100	26	" cast.....	21 100	0.0551
Osmium.....	19-08	0.0311	10	" fluid.....	250	0.0570
Palladium.....	-186 to +18	0.0528	26	" fluid.....	1100	0.0758
".....	0 100	0.0502	24	Titanium.....	185 to +20	0.082
".....	0-1205	0.0714	24	".....	0 100	0.1125
Phosphorus, red.....	0 51	0.1820	33	Tungsten.....	183 to +20	0.036
" yellow.....	13-36	0.202	33	".....	0 100	0.0330
" yellow.....	-186 to +20	0.178	4	".....	1000	0.0347
Platinum.....	-186 to +18	0.0203	26	".....	2000	0.042
".....	100	0.0275	34	".....	3400	0.045
".....	200	0.0330	35	Uranium.....	0 98	0.028
".....	500	0.0349	35	Vanadium.....	0 100	0.1153
".....	750	0.0395	35	Zinc.....	243	0.0444
".....	1000	0.0381	35	".....	-193	0.0625
".....	1300	0.0400	35	".....	143	0.0788
".....	20-100	0.0319	35	".....	20 100	0.0911
".....	20-500	0.0333	35	".....	100	0.0951
".....	20-1000	0.0340	35	".....	500	0.1040
".....	20-1300	0.0350	35	Zirconium.....	0 100	0.0600

\* When one temperature is given, the "true" specific heat is indicated, otherwise the "mean" specific page 226 for references.

## HEAT CAPACITIES. TRUE AND MEAN SPECIFIC HEATS. AND

## LATENT HEATS AT FUSION.

The following data are taken from a research and discussion entitled "Die Temperatur-Wärmeinhaltsskurven der technisch wichtigen Metalle," Wüst, Meuthen und Durrer, Forschungsarbeiten herausgegeben vom Verein Deutscher Ingenieure, Springer, Heft 204, 1918.

(a) There follow the constants of the equation for the heat capacity:  $W = a + bt + ct^2$ ; for the mean specific heat:  $s = at + b + ct$ ; and for the true specific heat:  $s' = b + 2ct$ ; also the latent heats at fusion. (See also Table 243, pp. 223-224.)

Element.	Temperature range, °C.	<i>a</i>	<i>b</i>	<i>c</i> × 10 <sup>6</sup>	Latent heat, cal./g.	Element.	Temperature range, °C.	<i>a</i>	<i>b</i>	<i>c</i> × 10 <sup>6</sup>	Latent heat, cal./g.
Cr	0-1500	—	0.10233	33.47	—	Ag	0-961	—	0.05725	5.48	26.0
Mo	0-1500	—	0.06162	10.99	—		961-1300	53.17	0.00710	28.30	—
W	0-1500	—	0.03325	1.07	—	Au	0-1064	—	0.03171	1.30	15.9
Pt	0-1500	—	0.03121	3.54	—		1064-1300	26.35	0.01420	8.52	—
Sn	0-232	—	0.06829	—	13.8	Cu	0-1084	—	0.10079	3.05	41.0
	232-1000	14.33	0.07020	-18.30	—		1084-1300	130.74	-0.04150	65.6	—
Bi	0-270	—	0.03141	5.22	10.2	Mn	0-1070	—	0.12037	25.41	36.6
	270-1000	10.31	0.03107	5.41	—		1130-1210	-7.41	0.17700	—	24.14*
Cd	0-321	—	0.05550	6.28	10.8		1230-1250	3.83	0.10800	—	—
	321-1000	6.30	0.06052	6.37	—	Ni	0-320	—	0.10950	52.40	56.1
Pb	0-327	—	0.03591	-11.47	5.47		320-1451	0.41	0.12031	0.11	1.33*
	327-1000	6.07	0.02020	3.30	—		1451-1520	50.21	0.13380	—	—
Zn	0-410	—	0.08777	43.48	23.0	Co	0-950	—	0.09119	40.77	58.2
	410-1000	14.34	0.13340	-16.10	—		1100-1478	22.00	0.11043	14.57	14.70*
Sb	0-630	—	0.05170	3.00	38.0		1478-1600	57.72	0.14720	—	—
	630-1000	39.42	0.05000	2.96	—	Fe	0-725	—	0.10545	56.84	49.4
Al	0-657	—	0.22200	38.57	94.0		725-919	-1.63	0.1592	—	6.56*
	657-1000	102.30	0.21870	24.00	—		919-1404	18.31	0.14472	0.05	6.67*
							1405-1528	-77.18	0.21416	—	1.94*
							1528-1600	70.03	0.15012	—	—

\* Allotropic heat of transformation: Mn, 1070-1130°; Ni, 320-330°; Co, 950-1100°; Fe, 725-785°; 919° = 1; 1404.5° = 0.5.

## (b) TRUE SPECIFIC HEATS.

°C	Pb	Zn	Al	Ag	Au	Cu	Ni	Fe	Co	Quartz.
0° C	0.0359	0.0878	0.2220	0.0573	0.0317	0.1008	0.1095	0.1055	0.0912	—
100	0.0330	0.0965	0.2207	0.0583	0.0320	0.1014	0.1200	0.1168	0.0993	0.2372
200	0.0313	0.1052	0.2374	0.0594	0.0322	0.1020	0.1305	0.1282	0.1073	0.2416
300	0.0290	0.1139	0.2451	0.0605	0.0325	0.1026	0.1409	0.1306	0.1154	0.2460
400	0.0266	0.1226	0.2529	0.0616	0.0328	0.1032	0.1294	0.1509	0.1235	0.2504
500	0.0250	0.1173	0.2606	0.0627	0.0330	0.1038	0.1294	0.1623	0.1316	0.2548
600	0.0252	0.1141	0.2683	0.0638	0.0333	0.1045	0.1294	0.1737	0.1396	0.2592
700	0.0246	0.1109	0.2523	0.0640	0.0335	0.1051	0.1295	0.1850	0.1477	0.2636
800	0.0239	0.1076	0.2571	0.0660	0.0338	0.1057	0.1295	0.1502	0.1558	0.2680
900	0.0233	0.1044	0.2610	0.0671	0.0341	0.1063	0.1295	0.1502	0.1630	0.2724
1000	0.0226	0.1012	0.2607	0.0637	0.0343	0.1069	0.1295	0.1448	—	0.2768
1100	—	—	—	0.0694	0.0329	0.1028	0.1296	0.1448	0.1424	0.2812
1200	—	—	—	0.0750	0.0346	0.1159	0.1296	0.1448	0.1454	0.2856
1300	—	—	—	0.0807	0.0364	0.1291	0.1296	0.1440	0.1483	0.2900
1400	—	—	—	—	—	—	0.1296	0.1440	0.1512	0.2944
1500	—	—	—	—	—	—	0.1338	0.2142	0.1472	0.2988
1600	—	—	—	—	—	—	—	0.1501	0.1472	—

For more elaborate tables and for all the elements in upper table, see original reference.

## ATOMIC HEATS (56° K). SPECIFIC HEATS (50° K). ATOMIC VOLUMES OF THE ELEMENTS.

The atomic and specific heats are due to Dewar, Pr. Roy. Soc. 89A, 168, 1913.

Element.	Specific heat -223° C.	Atomic heat -223° C.	Atomic volume.	Element.	Specific heat -223° C.	Atomic heat -223° C.	Atomic volume.	Element.	Specific heat -223° C.	Atomic heat -223° C.	Atomic volume.
Li	0.1924	1.35	13.0	Cr	0.0142	0.70	7.6	Sn	0.0286	3.41	20.3
Gl	0.0137	0.125	4.9	Mn	0.0229	1.26	7.4	Sb	0.0240	2.89	18.2
B	0.0212	0.24	4.5	Fe	0.0175	0.98	7.1	I	0.0361	4.59	25.7
C*	0.0137	0.16	5.1	Ni	0.0208	1.22	6.7	Te	0.0288	3.68	21.2
C†	0.0028	0.03	3.4	Co	0.0207	1.22	6.8	Cs	0.0513	6.82	71.0
Na	0.1519	3.50	23.6	Cu	0.0245	1.56	7.1	Ba¶	0.0350	4.80	36.6
Mg	0.0713	1.74	14.1	Zn	0.0384	2.52	9.2	La	0.0322	4.60	22.6
Al	0.0413	1.12	10.0	As	0.0258	1.94	15.9	Ce	0.0330	4.64	20.3
Si†	0.0303	0.86	14.2	Se	0.0361	2.86	18.5	W	0.0095	1.75	9.8
Si§	0.0303	0.77	11.4	Br	0.0453	3.62	24.9	Os	0.0078	1.49	8.5
P				Rb	0.0711	6.05	55.8	Ir	0.0099	1.92	8.6
yel.	0.0774	2.40	17.0	Sr¶	0.0550	4.82	34.5	Pt	0.0135	2.63	9.2
red				Zr	0.0262	2.38	21.8	Au	0.0160	3.16	10.2
S	0.0431	1.34	13.5	Mo	0.0141	1.36	9.3	Hg	0.0232	4.65	14.8
Cl	0.0546	1.75	16.	Ru	0.0109	1.11	9.0	Tl	0.0235	4.80	17.2
K	0.0967	3.43	24.6	Rh	0.0134	1.38	8.5	Pb	0.0240	4.96	18.3
Ca	0.1280	5.01	44.7	Pd	0.0190	2.03	9.2	Bi	0.0218	4.54	21.3
Ti	0.0714	2.86	25.9	Ag	0.0242	2.62	10.2	Th	0.0197	4.58	21.1
	0.0205	0.99	10.7	Cd	0.0308	3.46	13.0	U	0.0138	3.30	12.8

\* Graphite. † Diamond. ‡ Fused. § Crystallized. ¶ Impure.

## References to Table 243:

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TABLE 246.—Specific Heat of Various Solids.

Solids.	Temperature °C.	Specific heat.	Auth- ority.
Lead . . . . .	15-98	0.0858	R
Lead, red . . . . .	0	.08991	L
Lead, yellow . . . . .	0	.08831	"
Cu + 20 Sn . . . . .	14-98	.0862	R
Cu + 11.3 Al . . . . .	20-100	.10432	Ln
German silver . . . . .	0-100	.09464	T
Powitz alloy: 24.97 Pb + 10.13 Cd + 50.66 Bi + 14.24 Sn . . . . .	5-50	.0345	M
" . . . . .	100-150	.0426	"
Deville's alloy: 27.5 Pb + 48.9 Bi + 23.6 Sn . . . . .	-77-20	.0356	S
" . . . . .	20-89	.0552	"
Wood's alloy: 25.85 Pb + 6.99 Cd + 52.43 Bi + 14.73 Sn . . . . .	5-50	.0352	M
" (fluid) . . . . .	100-150	.0426	"
Various alloys:			
Sb + 29.9 Bi + 18.7 Zn + 33.9 Sn . . . . .	20-99	.05657	R
Sb + 62.9 Pb . . . . .	10-98	.03880	"
Pb + 60.1 Bi . . . . .	16-99	.03165	P
" (fluid) . . . . .	144-358	.03500	"
Pb + 36.3 Sn . . . . .	12-99	.04073	R
Pb + 53.3 Sn . . . . .	10-99	.04507	"
Bi + 36.2 Sn . . . . .	20-99	.04001	"
Bi + 53.1 Sn . . . . .	20-99	.04504	"
Al . . . . .	20-1040	.3145	—
Normal thermometer 16111 . . . . .	19-100	.1088	W
French hard thermometer . . . . .	—	.1869	Z
Crown . . . . .	10-50	.161	H M
Ant . . . . .	10-50	.117	"
" . . . . .	-188- -252	.146	D
" . . . . .	-78- -188	.285	"
" . . . . .	-18- -78	.463	"
Rubber (Para) . . . . .	?-100	.481	G T
" . . . . .	20	.10	—
" . . . . .	-20- +3	.3768	R W
" . . . . .	-19- +20	.5251	"
" . . . . .	0-20	.6939	"
" . . . . .	35-40	.622	B
Fluid . . . . .	60-63	.712	"
Ice . . . . .	20-100	.3312	A M
" . . . . .	20	.327	—

TABLE 247.—Specific Heat of Water and of Mercury.

Specific Heat of Water.					Specific Heat of Mercury.			
Barnes.	Rowland.	Barnes-Regnault.	Temperature, °C.	Barnes.	Barnes-Regnault.	Temperature, °C.	Specific Heat.	Specific Heat.
1.0155	—	—	60	0.9988	0.9994	0	0.03346	90
1.0091	1.0070	1.0094	65	.9994	1.0004	5	.03340	100
1.0050	1.0039	1.0053	70	1.0001	1.0015	10	.03335	110
1.0020	1.0016	1.0023	80	1.0014	1.0042	15	.03330	120
1.0000	1.0000	1.0003	90	1.0028	1.0070	20	.03325	130
0.9987	.9991	0.9990	100	1.0043	1.0101	25	.03320	140
.9978	.9989	.9981	120	—	1.0162	30	.03316	150
.9973	.9990	.9976	140	—	1.0223	35	.03312	170
.9971	.9997	.9974	160	—	1.0285	40	.03308	190
.9971	1.0006	.9974	180	—	1.0348	50	.03300	210
.9973	1.0018	.9976	200	—	1.0410	60	.03294	—
.9977	1.0031	.9980	220	—	1.0476	70	.03280	—
.9982	1.0045	.9985	—	—	—	80	.03284	—

Barnes's results: Phil. Trans. (A) 199, 1902; Phys. Rev. 15, 1902; 16, 1903. (H thermometer.)  
 Phil. Trans. A 211, p. 199, 1911. Barnes-Regnault's as revised by Peabody; Steam Tables.  
 data from 0° C to 80, Barnes-Cooke (H thermometer); from 90° to 140, mean of Winklemann, Naccari  
 and Mithaler (air thermometer); above 140°, mean of Naccari and Mithaler.

TABLE 248.—Specific Heat of Various Liquids.

Liquid.	Temp. ° C.	Spec. heat.	Auth- ority.	Liquid.	Temp. ° C.	Spec. heat.
Alcohol, ethyl.....	-20	0.5053	R	Ethyl ether.....	0	0.520
" ".....	0	0.548	"	Glycerine.....	15 50	0.570
" ".....	40	0.648	"	KOH + 30H <sub>2</sub> O.....	18	0.870
Alcohol, methyl.....	5-10	0.500	"	" + 100 ".....	18	0.975
" ".....	15-20	0.601	"	NaOH + 50H <sub>2</sub> O.....	18	0.942
Anilin.....	15	0.514	G	" + 100 ".....	18	0.983
" ".....	30	0.520	"	NaCl + 10H <sub>2</sub> O.....	18	0.701
" ".....	50	0.520	"	" + 200 ".....	18	0.978
Benzole, C <sub>6</sub> H <sub>6</sub> .....	10	0.340	H-I	Naphthalene, C <sub>10</sub> H <sub>8</sub> .....	80 85	0.306
" ".....	40	0.423	"	" ".....	90 95	0.400
" C <sub>6</sub> H <sub>6</sub> .....	65	0.482	"	Nitrobenzole.....	14	0.350
CaCl <sub>2</sub> , sp. gr. 1.14.....	-15	0.764	DMG	" ".....	28	0.362
" " " ".....	0	0.775	"	Oils: castor.....		0.434
" " " ".....	+20	0.787	"	" citron.....	5.4	0.438
" " " 1.20.....	-20	0.605	"	" olive.....	6.6	0.471
" " " ".....	0	0.712	"	" sesame.....		0.387
" " " ".....	+20	0.725	"	" turpentine.....	0	0.411
" " " 1.26.....	-20	0.651	"	Petroleum.....	21 58	0.511
" " " ".....	0	0.663	"	Sea water, sp. gr. 1.0043.....	17.5	0.980
" " " ".....	+20	0.676	"	" " " 1.0235.....	17.5	0.938
CuSO <sub>4</sub> + 50 H <sub>2</sub> O.....	12-15	0.848	Pa	" " " 1.0463.....	17.5	0.903
" + 200 ".....	12-14	0.951	"	Toluol, C <sub>6</sub> H <sub>5</sub> .....	10	0.364
" + 400 ".....	13-17	0.975	"	" ".....	65	0.490
Diphenylamine, C <sub>12</sub> H <sub>11</sub> N.....	53	0.464	B	" ".....	85	0.534
" ".....	65	0.482	"	ZnSO <sub>4</sub> + 50 H <sub>2</sub> O.....	20 52	0.842
				" + 200 ".....	20 52	0.952

References: (A) Abbot; (B) Batelli; (E) Emo; (G) Griffiths; (DMG) Dickir  
Mueller, and George; (H-I) de Heen and Deruyts; (Ma) Marignac; (Pa) Pagl  
(R) Regnault; (Th) Thomsen; (W) Wachsmuth; (Z) Zouloff; (HW) H. F. Webe

TABLE 249.—Specific Heat of Liquid Ammonia under Saturation Conditions.

Expressed in Calories<sub>20</sub> per Gram per Degree C. Osborne and van Dusen,  
Bul. Bureau of Standards, 1918.

Temp. ° C.	0	1	2	3	4	5	6	7	8
-40	1.062	1.061	1.060	1.059	1.058	1.058	1.057	1.056	1.055
-30	1.070	1.069	1.068	1.067	1.066	1.065	1.064	1.064	1.063
-20	1.078	1.077	1.076	1.075	1.074	1.074	1.073	1.072	1.071
-10	1.088	1.087	1.086	1.085	1.084	1.083	1.082	1.081	1.080
-0	1.099	1.098	1.097	1.096	1.094	1.093	1.092	1.091	1.090
+0	1.099	1.100	1.101	1.103	1.104	1.105	1.106	1.108	1.109
+10	1.112	1.113	1.114	1.116	1.117	1.118	1.120	1.122	1.123
+20	1.126	1.128	1.129	1.131	1.132	1.134	1.136	1.137	1.139
+30	1.142	1.144	1.146	1.148	1.150	1.152	1.154	1.156	1.158
+40	1.162	1.164	1.166	1.169	1.171	1.173	1.176	1.178	1.181

TABLE 250.—Heat Content of Saturated Liquid Ammonia.

Heat content =  $H = \epsilon + pv$ , where  $\epsilon$  is the internal or intrinsic energy. Osborne  
Dusen, Bul. Bureau of Standards, 1918.

Temperature...	-50°	-40°	-30°	-20°	-10°	0°	+10°	+20°	+30°	+40°
$H = \epsilon + pv$ .....	-53.8	-43.3	-32.6	-21.8	-11.0	0.0	+11.1	+22.4	+33.9	+45.5

## SPECIFIC HEATS OF MINERALS AND ROCKS.

TABLE 251.—Specific Heat of Minerals and Rocks.

Substance.	Temperature °C.	Specific Heat.	Reference.	Substance.	Temperature °C.	Specific Heat.	Reference.
Alusite . . .	0-100	.01684	1	Rock-salt . . .	13-45	.0219	6
Anhydrite, CaSO <sub>4</sub> . . .	0-100	.1753	1	Serpentine . . .	16-98	.2586	2
Asbestos . . .	15-99	.1903	2	Siderite . . .	9-98	.1934	4
Asbestos . . .	20-98	.195	3	Spinel . . .	15-47	.194	6
Asbestos . . .	20-98	.1931	3	Talc . . .	20-98	.2092	3
Barite, BaSO <sub>4</sub> . . .	10-98	.1128	4	Topaz . . .	0-100	.2097	1
Beryl . . .	15-99	.1979	2	Wollastonite . . .	19-51	.178	6
Borax, Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub> fused . . .	16-98	.2382	4	Zinc blende, ZnS . . .	0-100	.1146	1
Calcite, CaCO <sub>3</sub> . . .	0-50	.1877	1	Zircon . . .	21-51	.132	6
Calcite . . .	0-100	.2005	1	Rocks:			
Calcite . . .	0-300	.2204	1	Basalt, fine, black . . .	12-100	.1996	6
Chalcopyrite . . .	16-98	.0933	4	“ “ “ . . .	20-470	.199	9
Chalcopyrite . . .	15-99	.1291	2	“ “ “ . . .	470-750	.243	9
Chalcopyrite . . .	9-98	.1976	4	“ “ “ . . .	750-880	.626	9
Chalcopyrite . . .	16-99	.2522	2	“ “ “ . . .	880-1190	.323	9
Chalcopyrite . . .	15-99	.2154	4	Dolomite . . .	20-98	.222	3
Chalcopyrite . . .	0-100	.0466	5	Gneiss . . .	17-99	.196	10
Chalcopyrite . . .	16-100	.1758	2	“ . . .	17-213	.214	10
Chalcopyrite . . .	15-99	.1645	2	Granite . . .	12-100	.192	7
Chalcopyrite . . .	20-98	.1952	3	Kaolin . . .	20-98	.224	3
Chalcopyrite . . .	20-98	.1914	3	Lava, Aetna . . .	23-100	.201	11
Chalcopyrite . . .	20-98	.1949	3	“ . . .	31-776	.259	11
Chalcopyrite . . .	18-45	.156	6	“ Kilauea . . .	25-100	.197	11
Chalcopyrite . . .	15-99	.1763	2	Limestone . . .	15-100	.216	12
Chalcopyrite . . .	20-98	.2061	3	Marble . . .	0-100	.21	—
Chalcopyrite . . .	20-98	.2080	3	Quartz sand . . .	20-98	.191	3
Chalcopyrite . . .	20-98	.2048	3	Sandstone . . .	—	.22	—
Chalcopyrite . . .	15-99	.1877	2				
Chalcopyrite . . .	17-48	.159	6				
Chalcopyrite . . .	12-100	.188	7				
Chalcopyrite . . .	0	.1737	8				
Chalcopyrite . . .	350	.2786	8				
Chalcopyrite . . .	400-1200	.305	8				

1 Lindner. 6 Kopp. 11 Bartoli.  
 2 Oeberg. 7 Joly. 12 Morano.  
 3 Ulrich. 8 Pionchon.  
 4 Regnault. 9 Roberts-Austen, Rücker.  
 5 Tilden. 10 R. Weber.

Compiled from Landolt-Börnstein-Meyerhoffer's Physikalisch-chemische Tabellen.

TABLE 252.—Specific Heats of Silicates.

Silicate.	Mean specific heats. °C to				True specific heats. at				
	100°	500°	900°	1400°	0°C	100°	500°	1000°	1300°
te . . . . .	.1948	.2363	.2561	—	.178	.211	.269	.294	—
glass . . . . .	.1977	.2410	.2640	—	—	—	—	—	—
hibole, Mg. silicate . . . . .	.2033	.2461	.2661	.2731*	.185	.219	.279	.304	—
“ glass . . . . .	.2040	.2474	—	—	—	—	—	—	—
esine . . . . .	.1925	.2330	.2525	—	—	—	.265	—	—
“ glass . . . . .	.1934	—	.2615	—	—	—	—	—	—
orthite . . . . .	.1901	.2296	.02481	.2674	.174	.205	.260	.286	.318
“ glass . . . . .	.1883	.2305	—	—	—	—	—	—	—
obalite . . . . .	.1883	.2426	.2568	.2680	—	—	—	—	—
oside . . . . .	.1924	.2314	.2500	.2604†	.176	.207	.262	.284	—
“ glass . . . . .	.1939	.2332	—	—	—	—	—	—	—
ocline . . . . .	.1871	.2262	.2450	—	.171	.201	.258	.279	—
“ glass . . . . .	.1919	.2321	.2514	.2598*	.176	.206	.264	.299	—
oxene . . . . .	.2039	.2484	—	—	—	—	—	—	—
rtz . . . . .	.1868	.2379	.2596	.2640*	.168	.204	.294	.285	—
a glass . . . . .	.1845	.2302	.2512	—	.166	.202	.266	.29	—
lastonite . . . . .	—	—	.2344	—	—	—	—	—	—
“ glass . . . . .	.1852	.2206	—	—	—	—	—	—	—
“ pseudo . . . . .	.1844	.2170	.2324	.2448	.171	.197	.243	.262	.272

\*0°-1100°; †0°-1250°;

Taken from White, Am. J. Sc. 47, 1, 1919.

## SPECIFIC HEATS OF GASES AND VAPORS.

Substance.	Range of temp. °C	Sp. ht. constant pressure.	Authority.	Range of temp. °C	Mean ratio of specific heats, $C_p/C_v$ .	Authority.
Acetone, $C_3H_6O$ .....	26-110	0.3468	Wiedemann.			
Air.....	-30-+10	0.2377	Regnault.	20	1.4011	Moody.
".....	0-200	0.2375	"	-79.3	1.405	Koch, 1907.
".....	20-440	0.2366	Holborn and	-79.3	2.333	" " 200 atm
".....	20-630	0.2429	Austin.	0	1.828	" " "
".....	20-800	0.2430	"	500	1.399	Fürstenau.
Alcohol, $C_2H_5OH$ .....	108-220	0.4534	Regnault.	53	1.133	Jaeger.
".....	—	—	"	100	1.134	Stevens.
" $CH_3OH$ .....	101-223	0.4580	Regnault.	100	1.256	"
Ammonia.....	23-100	0.5202	Wiedemann.	0	1.3172	Wüllner.
".....	27-200	0.5356	"	100	1.2770	"
Argon.....	20-90	0.1233	Dittenberger.	0	1.667	Niemeyer.
Benzene, $C_6H_6$ .....	34-115	0.2990	Wiedemann.	20	1.403	Pagliani.
".....	35-180	0.3325	"	60	1.403	"
".....	116-218	0.3754	Regnault.	99.7	1.105	Stevens.
Bromine.....	83-228	0.5555	"	20-388	1.293	Strecker.
Carbon dioxide, $CO_2$ ...	-28-+7	0.1843	"	4-11	1.2995	Lummer and Pringsheim.
".....	15-100	0.2025	"	0	1.3003	Moody, 1912.
".....	11-214	0.2169	"	0	1.403	Wüllner.
" monoxide, $CO$ ...	23-99	0.2425	Wiedemann.	0	1.395	"
".....	26-198	0.2426	"	100	1.205	Beyme.
" disulphide, $CS_2$ ...	86-190	0.1596	Regnault.	3-67	1.336	Martini.
Chlorine.....	16-343	0.1125	Strecker.	0	1.102	Beyme.
Chloroform, $CHCl_3$ ...	27-118	0.1441	Wiedemann.	22-78	1.150	Stevens.
".....	28-189	0.1489	"	99.8	1.029	Müller.
Ether, $C_4H_{10}O$ .....	69-224	0.4797	Regnault.	42-45	1.024	Low, 1894.
".....	25-111	0.4280	Wiedemann.	12-20	1.64	Mean, Jeans.
Helium.....	—	—	—	0	1.389	Strecker.
Hydrochloric acid, $HCl$ ...	13-100	0.1940	Strecker.	20	1.400	"
".....	22-214	0.1867	Regnault.	100	1.4080	Lummer and Pringsheim.
Hydrogen.....	-28-+9	3.3996	"	4-16	1.410	Hartmann.
".....	12-108	3.4090	"	—	1.324	Capstick.
".....	21-100	3.4100	Wiedemann.	—	1.666	Ramsay, '12.
" sulphide, $H_2S$ ...	20-206	0.2451	Regnault.	10	1.666	Kundt and Warburg.
Krypton.....	—	—	—	310	1.316	Müller.
Mercury.....	—	—	—	—	1.642	Ramsay, '12
Methane, $CH_4$ .....	18-208	0.5929	Regnault.	11-30	1.41	Cazin.
Neon.....	—	—	—	10	1.405	Masson.
Nitrogen.....	0-200	0.2438	Regnault.	—	—	"
".....	20-440	0.2419	Holborn and	—	1.394	Natanson.
".....	20-630	0.2464	Austin.	—	1.31	"
".....	20-800	0.2497	"	—	—	"
Nitric oxide, $NO$ .....	13-172	0.2317	Regnault.	—	—	"
Nitrogen tetroxide, $NO_2$ ...	27-67	1.625	Berthelot and	—	—	"
".....	27-150	1.115	Olger.	—	—	"
".....	27-280	0.65	"	—	—	"
Nitrous oxide, $N_2O$ ...	16-207	0.2262	Regnault.	0	1.311	Wüllner.
".....	26-103	0.2126	Wiedemann.	100	1.272	"
".....	27-206	0.2241	"	—	1.324	Leduc, '98.
Oxygen.....	13-207	0.2175	Regnault.	5-14	1.3977	Lummer and Pringsheim.
".....	20-440	0.2240	Holborn and	—	—	"
".....	20-630	0.2300	Austin.	—	—	"
Sulphur dioxide, $SO_2$ ...	16-202	0.1544	Regnault.	16-34	1.256	Müller.
Water vapor, $H_2O$ .....	0	0.4655	Thiesen.	78	1.274	Beyme.
".....	100	0.421	"	94	1.33	Jaeger.
".....	180	0.51	"	100	1.305	Makower.
Xenon.....	—	—	—	19	1.666	Ramsay, '12.

## LATENT HEAT OF VAPORIZATION.

The temperature of vaporization in degrees Centigrade is indicated by  $t$ , the latent heat in large calories per kilogram or in small calories or therms per gram by  $r$ ; the total heat from  $0^{\circ}$  C, in the same units by  $H$ . The pressure is that due to the vapor at the temperature  $t$ .

Substance.	Formula.	$t^{\circ}$ C	$r$	$H$	Authority.
Acetic acid.....	$C_2H_4O_2$	$118^{\circ}$	84.9	—	Ogier.
Air.....	—	—	50.97	—	Fenner-Richtmyer.
Alcohol: Amyl.....	$C_5H_{12}O$	131	120	—	Schall.
Ethyl.....	$C_2H_6O$	78.1	205	255	Wirtz.
".....	"	0	236	236	Regnault.
".....	"	50	—	264	"
".....	"	100	—	267	"
".....	"	150	—	285	"
Methyl.....	$CH_3O$	64.5	267	307	Wirtz.
".....	"	0	289	289	Ramsay and Young.
".....	"	50	—	274	" " "
".....	"	100	—	246	" " "
".....	"	150	—	206	" " "
".....	"	200	—	152	" " "
".....	"	238.5	—	44.2	" " "
Aniline.....	$C_6H_7N$	184	110	—	Mean.
Benzene.....	$C_6H_6$	80.1	92.9	127.9	Wirtz.
Bromine.....	Br	61	45.6	—	Andrews.
Carbon dioxide, solid....	$CO_2$	—	—	138.7	Favre.
" " liquid....	"	-25	72.23	—	Cailletet and Mathias.
" " ".....	"	0	57.48	—	" " "
" " ".....	"	12.35	44.97	—	Mathias.
" " ".....	"	22.04	31.8	—	"
" " ".....	"	29.85	14.4	—	"
" " ".....	"	30.82	3.72	—	"
" disulphide.....	$CS_2$	46.1	83.8	94.8	Wirtz.
" ".....	"	0	90	90	Regnault.
" ".....	"	100	—	100.5	"
" ".....	"	140	—	102.4	"
Chloroform.....	$CHCl_3$	60.9	58.5	72.8	Wirtz.
Ether.....	$C_4H_{10}O$	34.5	88.4	107	"
".....	"	34.9	90.5	—	Andrews.
".....	"	0	94	94	Regnault.
".....	"	50	—	115.1	"
".....	"	120	—	140	"
Ethyl bromide.....	$C_2H_5Br$	38.2	60.4	—	Wirtz.
chloride.....	$C_2H_5Cl$	12.5	—	98	Regnault.
iodide.....	$C_2H_5I$	71	47	—	Mean.
Heptane.....	$C_7H_{16}$	90	77.8	—	Young.
Hexane.....	$C_6H_{14}$	70	79.2	—	"
Iodine.....	I	—	23.95	—	Favre and Silbermann.
Mercury.....	Hg	357.	65	—	Mean.
Nitrogen.....	$N_2$	-195.6	47.65	—	Alt.
Octane.....	$C_8H_{18}$	130	70.0	—	Young.
Oxygen.....	$O_2$	-182.9	50.97	—	Alt.
Pentane.....	$C_5H_{12}$	30	85.8	—	Young.
Sulphur.....	S	316	362.0	—	Person.
Sulphur dioxide.....	$SO_2$	0	91.2	—	Cailletet and Mathias.
".....	"	30	80.5	—	" " "
".....	"	65	68.4	—	" " "
Toluene.....	$C_7H_8$	111	86.0	—	Mean.
Turpentine.....	$C_{10}H_{10}$	159.3	74.04	—	Brix.

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# INTRODUCTION.

## UNITS OF MEASUREMENT. DIMENSIONAL AND CONVERSION FORMULAE.

The quantitative measure of anything is expressed by two factors, one, a certain definite amount of the kind of physical quantity measured, called the unit, the other, the number of times this unit is taken. A distance is stated as 5 meters. The purpose in such a statement is to convey an idea of this distance in terms of some familiar or standard unit distance. Similarly quantity of matter is referred to as so many grams; of time, as so many seconds, or minutes, or hours.

The numerical factor definitive of the magnitude of any quantity must depend on the size of the unit in terms of which the quantity is measured. For example, let the magnitude factor be 5 for a certain distance when the mile is used as the unit of measurement. A mile equals 1760 yards or 5280 feet. The numerical factor evidently becomes 8800 and 26400, respectively, when the yard or the foot is used as the unit. Hence, to obtain the magnitude factor for a quantity in terms of a new unit, multiply the old magnitude factor by the ratio of the magnitudes of the old and new units; that is, by the number of the new units required to make one of the old.

The different kinds of quantities measured by physicists fall fairly definitely into two classes. In one class the magnitudes may be called extensive, — in the other, intensive. To decide to which class a quantity belongs, it is often helpful to note the effect of the addition of two equal quantities of the kind in question. If twice the quantity results, then the quantity has extensive (additive) magnitude. For instance, two pieces of platinum, each weighing 5 grams, added together, weigh 10 grams; on the other hand, the addition of one piece of platinum at 100° C to another at 100° C does not result in a system at 200° C. Volume, entropy, energy may be taken as typical of extensive, — density, temperature and magnetic permeability, of intensive magnitudes.

The measurement of quantities having extensive magnitude is a comparatively direct process. Those having intensive magnitude must be correlated with phenomena which may be measured extensively. In the case of temperature, a typical quantity with intensive magnitude, various methods of measurement have been devised, such as the correlation of magnitudes of temperature with the varying lengths of a thread of mercury.

**Fundamental Units.** — It is desirable that the fewest possible fundamental unit quantities should be chosen. Simplicity should regulate the choice, — simplicity 1st, psychologically, in that they should be easy to grasp mentally, and 2nd, physically, in permitting as straightforward and simple definition as

possible of the complex relationships involving them. Further it seems desirable that the units should be extensive in nature. It has been found possible to express all measurable physical quantities in terms of five such units: 1st, geometrical considerations — length, surface, etc., — lead to the need of a length; 2nd, kinematical considerations — velocity, acceleration, etc., — introduce time; 3rd, mechanics — treating of masses instead of immaterial points — introduces matter with the need of a fundamental unit of mass; 4th, electrical, and 5th, thermal considerations require two more such quantities. The discovery of new classes of phenomena may require further additions.

As to the first three fundamental quantities, simplicity and good use sanction the choice of a length,  $L$ , a time interval,  $T$ , and a mass,  $M$ . For the measurement of electrical quantities, good use has sanctioned two fundamental quantities, — the dielectric constant,  $K$ , the basis of the “electrostatic” system and the magnetic permeability,  $\mu$ , the basis of the “electromagnetic” system. Besides these two systems involving electrical considerations, there is in common use a third one called the “international” system which will be referred to later. For the fifth, or thermal fundamental unit, temperature is generally chosen.<sup>1</sup>

**Derived Units.** — Having selected the fundamental or basic units, — namely, a measure of length, of time, of mass, of permeability or of the dielectric constant, and of temperature, — it remains to express all other units for physical quantities in terms of these. Units depending on powers greater than unity of the basic units are called “derived units.” Thus, the unit volume is the volume of a cube having each edge a unit of length. Suppose that the capacity of some volume is expressed in terms of the foot as fundamental unit and the volume number is wished when the yard is taken as the unit. The yard is three times as long as the foot and therefore the volume of a cube whose edge is a yard is  $3 \times 3 \times 3$  times as great as that whose edge is a foot. Thus the given volume will contain only  $1/27$  as many units of volume when the yard is the unit of length as it will contain when the foot is the unit. To transform from the foot as old unit to the yard as new unit, the old volume number must be multiplied by  $1/27$ , or by the ratio of the magnitude of the old to that of the new unit of volume. This is the same rule as already given, but it is usually more convenient to express the transformations in terms of the fundamental units directly. In the present case, since, with the method of measurement here adopted, a volume number is the cube of a length-number, the ratio of two units of volume is the cube of the ratio of the intrinsic values of the two units of length. Hence, if  $l$  is the ratio of the magnitude of the old to that of the new unit of length, the ratio of the corresponding units of volume is  $l^3$ . Similarly the ratio of two units of area would be  $l^2$ , and so on for other quantities.

<sup>1</sup> Because of its greater psychological and physical simplicity, and the desirability that the unit chosen should have extensive magnitude, it has been proposed to choose as the fourth fundamental quantity, a quantity of electrical charge,  $e$ . The standard unit of electrical charge would then be the electronic charge. For thermal needs, entropy has been proposed. While not generally so psychologically easy to grasp as temperature, entropy is of fundamental importance in thermodynamics and has extensive magnitude. (R. C. Tolman, *The Measurable Quantities of Physics*, Physical Review, 9, p. 237, 1917.)



**Conversion Factors and Dimensional Formulae.** — For the ratios of length, mass, time, temperature, dielectric constant and permeability units the small bracketed letters,  $[L]$ ,  $[m]$ ,  $[t]$ ,  $[\theta]$ ,  $[k]$ , and  $[\mu]$  will be adopted. These symbols will always represent simple numbers, but the magnitude of the number will depend on the relative magnitudes of the units the ratios of which they represent. When the values of the numbers represented by these small bracketed letters as well as the powers of them involved in any particular unit are known, the factor for the transformation is at once obtained. Thus, in the above example, the value of  $l$  was  $1/3$ , and the power involved in the expression for volume was 3; hence the factor for transforming from cubic feet to cubic yards was  $l^3$  or  $1/3^3$  or  $1/27$ . These factors will be called *conversion factors*.

To find the symbolic expression for the conversion factor for any physical quantity, it is sufficient to determine the degree to which the quantities length, mass, time, etc., are involved. Thus a velocity is expressed by the ratio of the number representing a length to that representing an interval of time, or  $[L/T]$ , and acceleration by a velocity number divided by an interval-of-time number, or  $[L/T^2]$ , and so on, and the corresponding ratios of units must therefore enter in precisely the same degree. The factors would thus be for the just stated cases,  $[l/t]$  and  $[l/t^2]$ . Equations of the form above given for velocity and acceleration which show the dimensions of the quantity in terms of the fundamental units are called *dimensional equations*. Thus  $[E] = [ML^2T^{-2}]$  will be found to be the dimensional equation for energy, and  $[ML^2T^{-2}]$  the dimensional formula for it. These expressions will be distinguished from the conversion factors by the use of bracketed capital letters.

In general, if we have an equation for a physical quantity,

$$Q = C L^a M^b T^c,$$

where  $C$  is a constant and  $L$ ,  $M$ ,  $T$  represent length, mass, and time in terms of one set of units, and it is desired to transform to another set of units in terms of which the length, mass, and time are  $L_1$ ,  $M_1$ ,  $T_1$ , we have to find the value of  $L_1/L$ ,  $M_1/M$ ,  $T_1/T$ , which, in accordance with the convention adopted above, will be  $l$ ,  $m$ ,  $t$ , or the ratios of the magnitudes of the old to those of the new units.

Thus  $L_1 = Ll$ ,  $M_1 = Mm$ ,  $T_1 = Tt$ , and if  $Q_1$  be the new quantity number,

$$\begin{aligned} Q_1 &= C L_1^a M_1^b T_1^c, \\ &= C L^a l^a M^b m^b T^c t^c = Q l^a m^b t^c, \end{aligned}$$

or the conversion factor is  $[l^a m^b t^c]$ , a quantity precisely of the same form as the dimensional formula  $[L^a M^b T^c]$ .

Dimensional equations are useful for checking the validity of physical equations. Since physical equations must be homogeneous, each term appearing in them must be dimensionally equivalent. For example, the distance moved by a uniformly accelerated body is  $s = v_0 t + \frac{1}{2} a t^2$ . The corresponding dimensional equation is  $[L] = [(L/T)T] + [(L/T^2)T^2]$ , each term reducing to  $[L]$ .

Dimensional considerations may often give insight into the laws regulating physical phenomena.<sup>1</sup> For instance Lord Rayleigh, in discussing the intensity

<sup>1</sup> See "On Physically Similar Systems; Illustrations of the Use of Dimensional Equations," E. Buckingham, *Physical Review*, (2) 4, p. 345, 1914.

of light scattered from small particles, in so far as it depends upon the wave-length, reasons as follows:<sup>1</sup>

"The object is to compare the intensities of the incident and scattered ray; for these will clearly be proportional. The number ( $i$ ) expressing the ratio of the two amplitudes is a function of the following quantities:—  $T$ , the volume of the disturbing particle;  $r$ , the distance of the point under consideration from it;  $\lambda$ , the wave-length;  $b$ , the velocity of propagation of light;  $D$  and  $D'$ , the original and altered densities: of which the first three depend only on space, the fourth on space and time, while the fifth and sixth introduce the consideration of mass. Other elements of the problem there are none, except mere numbers and angles, which do not depend upon the fundamental measurements of space, time, and mass. Since the ratio  $i$ , whose expression we seek, is of no dimensions in mass, it follows at once that  $D$  and  $D'$  occur only under the form  $D:D'$ , which is a simple number and may therefore be omitted. It remains to find how  $i$  varies with  $T, r, \lambda, b$ .

"Now, of these quantities,  $b$  is the only one depending on time; and therefore, as  $i$  is of no dimensions in time,  $b$  cannot occur in its expression. We are left, then, with  $T, r$ , and  $\lambda$ ; and from what we know of the dynamics of the question, we may be sure that  $i$  varies directly as  $T$  and inversely as  $r$ , and must therefore be proportional to  $T : \lambda^2 r$ ,  $T$  being of three dimensions in space. In passing from one part of the spectrum to another  $\lambda$  is the only quantity which varies, and we have the important law:

"When light is scattered by particles which are very small compared with any of the wave-lengths, the ratio of the amplitudes of the vibrations of the scattered and incident light varies inversely as the square of the wave-length, and the intensity of the lights themselves as the inverse fourth power."

The dimensional and conversion-factor formulae for the more commonly occurring derived units will now be developed.

**Area** is referred to a unit square whose side is the unit of length. The area of a surface is expressed as

$$S = C L^2,$$

where the constant  $C$  depends on the contour of the surface and  $L$  is a linear dimension. If the surface is a square and  $L$  the length of a side,  $C$  is unity; if a circle and  $L$  its diameter,  $C$  is  $\pi/4$ . The dimensional formula is therefore  $[L^2]$  and the conversion factor  $[l^2]$ . (Since the conversion factors are always of the same dimensions as the dimensional formulae they will be omitted in the subsequent discussions. A table of them will be found on page 3.)

**Volume** is referred to a unit cube whose edge is the unit of length. The volume of a body is expressed as

$$V = C L^3.$$

The constant  $C$  depends on the shape of the bounding surfaces. The dimensional formula is  $[L^3]$ .

**Density** is the quantity of matter per unit volume. The dimensional formula is  $[M/V]$  or  $[ML^{-3}]$ .

Ex.—The density of a body is 150 pd. per cu. ft.: required the density in grains per cu. in. Here  $m$ , the number of grains in a pd., = 7000;  $l$ , the number of in. in a ft., = 12;  $ml^3$  =  $7000/12^3$  = 4.051. The density is  $150 \times 4.051$  = 607.6 grains/cu. in.

The specific gravity of a body is the ratio of a density to the density of a standard substance. The dimensional formula and conversion factor are both unity.

<sup>1</sup> Philosophical Magazine, (4) 41, p. 107, 1871.

**Velocity,  $v$ ,** of a body is  $dL/dt$ , or the ratio of a length to a time. The dimensional formula is  $[LT^{-1}]$ .

**Angle** is measured by the ratio of the length of an arc to its radius. The dimensional formula is unity.

**Angular Velocity** is the ratio of the angle described in a given time to that time. The dimensional formula is  $[T^{-1}]$ .

**Linear Acceleration** is the rate of change of velocity or  $a = dv/dt$ . The dimensional formula is  $[VT^{-1}]$  or  $[LT^{-2}]$ .

Ex. — A body acquires velocity at a uniform rate and at the end of one minute moves at the rate of 20 kilometers per hour: what is the acceleration in centimeters per second per second? Since the velocity gained was 20 km per hour in one minute, the acceleration was 1200 km per hour per hour.  $l = 100000$ ,  $t = 3600$ ,  $lt^{-2} = 100000/3600^2 = 0.00771$ ; the acceleration =  $0.00771 \times 1200 = 9.26$  cm/sec.

**Angular Acceleration** is rate of change of angular velocity. The dimensional formula is  $[(\text{angular velocity})/T]$  or  $[T^{-2}]$ .

**Momentum**, the quantity of motion in the Newtonian sense, is measured by the product of the mass and velocity of the body. The dimensional formula is  $[MV]$  or  $[MLT^{-1}]$ .

**Moment of Momentum** of a body with reference to a point is the product of its momentum by the distance of its line of motion from the point. The dimensional formula is  $[ML^2T^{-1}]$ .

**Moment of Inertia** of a body round an axis is expressed by the formula  $\sum mr^2$ , where  $m$  is the mass of any particle of the body and  $r$  its distance from the axis. The dimensional formula for the sum is the same as for each element and is  $[ML^2]$ .

**Angular Momentum** of a body is the product of its moment of inertia and angular velocity. The dimensional formula is  $[ML^2T^{-1}]$ .

**Force** is measured by the rate of change of momentum it can produce. The dimensional formulae for force and "time rate of change of momentum" are therefore the same, the ratio of a momentum to a time  $[MLT^{-2}]$ .

Ex. — When mass is expressed in lbs., length in ft., and time in secs., the unit force is called the poundal. When grams, cms, and secs. are the corresponding units, the unit of force is called the dyne. Find the number of dynes in 25 poundals. Here  $m = 453.59$ ,  $l = 30.48$ ,  $t = 1$ ;  $mlt^{-2} = 453.59 \times 30.48 = 13825$  nearly. The number of dynes is  $13825 \times 25 = 345625$  approximately.

**Moment of Couple, Torque, or Twisting Motive** can be expressed as the product of a force and a length. The dimensional formula is  $[FL]$  or  $[ML^2T^{-2}]$ .

**Intensity of Stress** is the ratio of the total stress to the area over which the stress is distributed. The dimensional formula is  $[FL^{-2}]$  or  $[ML^{-1}T^{-2}]$ .

**Intensity of Attraction, or "Force at a Point,"** is the force of attraction per unit mass on a body placed at the point. The dimensional formula is  $[FM^{-1}]$  or  $[LT^{-2}]$ , the same as acceleration.

**Absolute Force of a Center of Attraction**, or "**Strength of a Center**," is the intensity of force at unit distance from the center, and is the force per unit mass at any point multiplied by the square of the distance from the center. The dimensional formula is  $[FL^2M^{-1}]$  or  $[L^3T^{-2}]$ .

**Modulus of Elasticity** is the ratio of stress intensity to percentage strain. The dimensional of percentage strain, a length divided by a length, is unity. Hence the dimensional formula of a modulus of elasticity is that of stress intensity  $[ML^{-1}T^{-2}]$ .

**Work** is done by a force when the point of application of the force, acting on a body, moves in the direction of the force. It is measured by the product of the force and the displacement. The dimensional formula is  $[FL]$  or  $[ML^2T^{-2}]$ .

**Energy**. — The work done by the force produces either a change in the velocity of the body or a change of its shape or configuration, or both. In the first case it produces a change of kinetic energy, in the second, of potential energy. The dimensional formulae of energy and work, representing quantities of the same kind, are identical  $[ML^2T^{-2}]$ .

**Resilience** is the work done per unit volume of a body in distorting it to the elastic limit or in producing rupture. The dimensional formula is  $[ML^2T^{-2}L^{-3}]$  or  $[ML^{-1}T^{-2}]$ .

**Power or Activity** is the time rate of doing work, or if  $W$  represents work and  $P$  power,  $P = dw/dt$ . The dimensional formula is  $[WT^{-1}]$  or  $[ML^2T^{-3}]$ , or for problems in gravitation units more conveniently  $[FLT^{-1}]$ , where  $F$  stands for the force factor.

**Exs.** — Find the number of gram-cms in one ft.-pd. Here the units of force are the attraction of the earth on the pound and the gram of matter. (In problems like this the terms "grams" and "pd." refer to force and not to mass.) The conversion factor is  $[g]$ , where  $g$  is 453.59 and  $l$  is 30.48. The answer is  $453.59 \times 30.48 = 13825$ .

Find the number of ft.-poundals in 1000000 cm-dynes. Here  $m = 1/453.59$ ,  $l = 1/30.48$ ,  $t = 1$ ;  $m^2l^{-2} = 1/453.59 \times 30.48^2$ , and  $10^6 m^2 l^{-2} = 10^6 / 453.59 \times 30.48^2 = 2.473$ .

If gravity produces an acceleration of 32.2 ft./sec./sec., how many watts are required to make one horse-power? One horse-power is 550 ft.-pds. per sec., or  $550 \times 32.2 = 17710$  ft. poundals per second. One watt is  $10^7$  ergs per sec., that is,  $10^7$  dyne-cms per sec. The conversion factor is  $[m^2l^{-2}]$ , where  $m$  is 453.59,  $l$  is 30.48, and  $t$  is 1, and the result has to be divided by  $10^7$ , the number of dyne-cms per sec. in the watt.  $17710 m^2 l^{-2} / 10^7 = 17710 \times 453.59 \times 30.48^2 / 10^7 = 746.3$ .

## HEAT UNITS.

**Quantity of Heat**, measured in dynamical units, has the same dimensions as energy  $[ML^2T^{-2}]$ . Ordinary measurements, however, are made in *thermal units*, that is, in terms of the amount of heat required to raise the temperature of a unit mass of water one degree of temperature at some stated temperature. This involves the unit of mass and some unit of temperature. If we denote temperature numbers by  $\Theta$ , the dimensional formula for quantity of heat,  $H$ , will be  $[M\Theta]$ . Unit volume is sometimes used instead of unit mass in the measurement of heat, the units being called *thermometric units*. The dimensional formula now changed by the substitution of volume for mass is  $[L^3\Theta]$ .

**Specific Heat** is the relative amount of heat, compared with water as standard substance, required to raise unit mass of different substances one degree in temperature and is a simple number.

**Coefficient of Thermal Expansion** of a substance is the ratio of the change of length per unit length (linear), or change of volume per unit volume (voluminal), to the change of temperature. These ratios are simple numbers, and the change of temperature varies inversely as the magnitude of the unit of temperature. The dimensional formula is  $[\Theta^{-1}]$ .

**Thermal Conductivity**, or **Specific Conductance**, is the quantity of heat,  $H$ , transmitted per unit of time per unit of surface per unit of temperature gradient. The equation for conductivity is therefore  $K = H/L^2T\Theta/L$ , and the dimensional formula  $[H/\Theta LT] = [ML^{-1}T^{-1}]$  in thermal units. In thermometric units the formula becomes  $[L^2T^{-1}]$ , which properly represents diffusivity, and in dynamical units  $[MLT^{-3}\Theta^{-1}]$ .

**Thermal Capacity** is mass times the specific heat. The dimensional formula is  $[M]$ .

**Latent Heat** is the quantity of heat required to change the state of a body divided by the quantity of matter. The dimensional formula is  $[M\Theta/M]$  or  $[\Theta]$ ; in dynamical units it is  $[L^2T^{-2}]$ .

NOTE. — When  $\Theta$  is given the dimensional formula  $[L^2T^{-2}]$ , the formulae in thermal and dynamical units are identical.

**Joule's Equivalent**,  $J$ , is connected with the quantity of heat by the equation  $ML^2T^{-2} = JH$  or  $JM\Theta$ . The dimensional formula of  $J$  is  $[L^2T^{-2}\Theta^{-1}]$ . In dynamical units  $J$  is a simple number.

**Entropy** of a body is directly proportional to the quantity of heat it contains and inversely proportional to its temperature. The dimensional formula is  $[M\Theta/\Theta]$  or  $[M]$ . In dynamical units the formula is  $[ML^2T^{-2}\Theta^{-1}]$ .

EXS. — Find the relation between the British thermal unit, the large or kilogram-calorie and the small or gram-calorie, sometimes called the "therm." Referring all the units to the same temperature of the standard substance, the *British thermal unit* is the amount of heat required to warm one pound of water  $1^\circ\text{C}$ , the *large calorie*, 1 kilogram of water,  $1^\circ\text{C}$ , the *small calorie* or *therm*, 1 gram,  $1^\circ\text{C}$ . (1) To find the number of kg-cals. in one British thermal unit.  $m = .45359$ ,  $\theta = 5/9$ ;  $m\theta = .45359 \times 5/9 = .25199$ . (2) To find the number therms in one kg-cal.  $m = 1000$ , and  $\theta = 1$ ;  $m\theta = 1000$ . (3) Hence the number of small calories or therms in one British thermal unit is  $1000 \times .25199 = 251.99$ .

## ELECTRIC AND MAGNETIC UNITS.

A system of units of electric and magnetic quantities requires four fundamental quantities. A system in which length, mass, and time constitute three of the fundamental quantities is known as an "absolute" system. There are two absolute systems of electric and magnetic units. One is called the electrostatic, in which the fourth fundamental quantity is the dielectric constant, and one is called the electromagnetic, in which the fourth fundamental quantity is magnetic permeability. Besides these two systems there will be described a third in common use called the "international" system.

In the electrostatic system, unit quantity of electricity,  $Q$ , is the quantity which exerts unit mechanical force upon an equal quantity a unit distance from it in a vacuum. From this definition the dimensions and the units of all the other electric and magnetic quantities follow through the equations of the mathematical theory of electromagnetism. The mechanical force between two quantities of electricity in any medium is

$$F = \frac{QQ'}{Kr^2},$$

where  $K$  is the dielectric constant, characteristic of the medium, and  $r$  the distance between the two points at which the quantities  $Q$  and  $Q'$  are located.  $K$  is the fourth quantity entering into dimensional expressions in the electrostatic system. Since the dimensional formula for force is  $[MLT^{-2}]$ , that for  $Q$  is  $[M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}K^{\frac{1}{2}}]$ .

The electromagnetic system is based upon the unit of the magnetic pole strength. The dimensions and the units of the other quantities are built up from this in the same manner as for the electrostatic system. The mechanical force between two magnetic poles in any medium is

$$F = \frac{mm'}{\mu r^2},$$

in which  $\mu$  is the permeability of the medium and  $r$  is the distance between two poles having the strengths  $m$  and  $m'$ .  $\mu$  is the fourth quantity entering into dimensional expressions in the electromagnetic system. It follows that the dimensional expression for magnetic pole strength is  $[M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-\frac{1}{2}}\mu^{\frac{1}{2}}]$ .

The symbols  $K$  and  $\mu$  are sometimes omitted in the dimensional formulae so that only three fundamental quantities appear. There are a number of objections to this. Such formulae give no information as to the relative magnitudes of the units in the two systems. The omission is equivalent to assuming some relation between mechanical and electrical quantities, or to a mechanical explanation of electricity. Such a relation or explanation is not known.

The properties  $K$  and  $\mu$  are connected by the equation  $1/\sqrt{K\mu} = v$ , where  $v$  is the velocity of an electromagnetic wave. For empty space or for air,  $K$  and  $\mu$  being measured in the same units,  $1/\sqrt{K\mu} = c$ , where  $c$  is the velocity of light in vacuo,  $3 \times 10^{10}$  cm per sec. It is sometimes forgotten that the omission of the dimensions of  $K$  or  $\mu$  is merely conventional. For instance, magnetic field intensity and magnetic induction apparently have the same dimensions when  $\mu$  is omitted. This results in confusion and difficulty in understanding the theory of magnetism. The suppression of  $\mu$  has also led to the use of the "centimeter" as a unit of capacity and of inductance; neither is physically the same as length.

## ELECTROSTATIC SYSTEM.

**Quantity of Electricity** has the dimensional formula  $[M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}K^{\frac{1}{2}}]$ , as shown above.

**Electric Surface Density** of an electrical distribution at any point on a surface is measured by the quantity per unit area. The dimensional formula is the ratio of the formulae for quantity of electricity and for area or  $[M^{\frac{1}{2}}L^{-\frac{1}{2}}T^{-1}K^{\frac{1}{2}}]$ .

**Electric Field Intensity** is measured by the ratio of the force on a quantity of electricity at a point to the quantity of electricity. The dimensional formula is therefore the ratio of the formulae for force and electric quantity or  $[MLT^{-2}/M^{1/2}L^{3/2}T^{-1}K^{1/2}]$  or  $[M^{1/2}L^{1/2}T^{-1}K^{-1/2}]$ .

**Electric Potential and Electromotive Force.** — Change of potential is proportional to the work done per unit of electricity in producing the change. The dimensional formula is the ratio of the formulae for work and electrical quantity or  $[ML^2T^{-2}/M^{1/2}L^{3/2}T^{-1}K^{1/2}]$  or  $[M^{1/2}L^{3/2}T^{-1}K^{1/2}]$ .

**Capacity of an Insulated Conductor** is proportional to the ratio of the quantity of electricity in a charge to the potential of the charge. The dimensional formula is the ratio of the two formulae for electric quantity and potential or  $[M^{1/2}L^{3/2}T^{-1}K^{1/2}/M^{1/2}L^{3/2}T^{-1}K^{1/2}]$  or  $[LK]$ .

**Specific Inductive Capacity** is the ratio of the inductive capacity of the substance to that of a standard substance and therefore is a number.

**Electric Current** is quantity of electricity flowing past a point per unit of time. The dimensional formula is the ratio of the formulae for electric quantity and for time or  $[M^{1/2}L^{3/2}T^{-1}K^{1/2}/T]$  or  $[M^{1/2}L^{3/2}T^{-2}K^{1/2}]$ .

**Electrical Conductivity**, like the corresponding term for heat, is quantity per unit area per unit potential gradient per unit of time. The dimensional formula is  $[M^{1/2}L^{3/2}T^{-1}K^{1/2}/L^2(M^{1/2}L^{3/2}T^{-1}K^{1/2}/L)T]$  or  $[T^{-1}K]$ .

**Resistivity** is the reciprocal of conductivity. The dimensional formula is  $[TK^{-1}]$ .

**Conductance** of any part of an electric circuit, not containing a source of electromotive force, is the ratio of the current flowing through it to the difference of potential between its ends. The dimensional formula is the ratio of the formulae for current and potential or  $[M^{1/2}L^{3/2}T^{-2}K^{1/2}/M^{1/2}L^{3/2}T^{-1}K^{1/2}]$  or  $[LT^{-1}K]$ .

**Resistance** is the reciprocal of conductance. The dimensional formula is  $[L^{-1}TK^{-1}]$ .

**Exs.** — Find the factor for converting quantity of electricity expressed in ft. grain-sec. units to the same expressed in c.g.s. units. The formula is  $[m^{1/2}l^{3/2}t^{-1}k^{1/2}]$ , in which  $m = 0.0648$ ,  $l = 30.48$ ,  $t = 1$ ,  $k = 1$ ; the factor is  $0.0648^{1/2} \times 30.48^{3/2}$ , or 42.8.

Find the factor required to convert electric potential from mm.-mg.-sec. units to c.g.s. units. The formula is  $[m^{1/2}l^{3/2}t^{-1}k^{1/2}]$ , in which  $m = 0.001$ ,  $l = 0.1$ ,  $t = 1$ ,  $k = 1$ ; the factor is  $0.001^{1/2} \times 0.1^{3/2}$ , or 0.01.

Find the factor required to convert electrostatic capacity from ft.-grain-sec. and specific inductive capacity 6 units to c.g.s. units. The formula is  $[lk]$  in which  $l = 30.48$ ,  $k = 6$ ; the factor is  $30.48 \times 6$ , or 182.88.

## ELECTROMAGNETIC SYSTEM.

Many of the magnetic quantities are analogues of certain electric quantities. The dimensions of such quantities in the electromagnetic system differ from those of the corresponding electrostatic quantities in the electrostatic system only in the substitution of permeability  $\mu$  for  $K$ .

**Magnetic Pole Strength** or **Quantity of Magnetism** has already been shown to have the dimensional formula  $[M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}\mu^{\frac{1}{2}}]$ .

**Magnetic Flux** characterizes the magnetized state of a magnetic circuit. Through a surface inclosing a magnetic pole it is proportional to the magnetic pole strength. The dimensional formula is that for magnetic pole strength.

**Magnetic Field Intensity** or **Magnetizing Force** is the ratio of the force on a magnetic pole placed at the point and the magnetic pole strength. The dimensional formula is therefore the ratio of the formulae for a force and magnetic quantity, or  $[MLT^{-2}/M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}\mu^{\frac{1}{2}}]$  or  $[M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}\mu^{-\frac{1}{2}}]$ .

**Magnetic Potential** or **Magnetomotive Force** at a point is measured by the work which is required to bring unit quantity of positive magnetism from zero potential to the point. The dimensional formula is the ratio of the formulae for work and magnetic quantity,  $[ML^2T^{-2}/M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}\mu^{\frac{1}{2}}]$  or  $[M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}\mu^{\frac{1}{2}}]$ .

**Magnetic Moment** is the product of the pole strength by the length of the magnet. The dimensional formula is  $[M^{\frac{1}{2}}L^{\frac{5}{2}}T^{-1}\mu^{\frac{1}{2}}]$ .

**Intensity of Magnetization** of any portion of a magnetized body is the ratio of the magnetic moment of that portion and its volume. The dimensional formula is  $[M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}\mu^{\frac{1}{2}}/L^3]$  or  $[M^{\frac{1}{2}}L^{-\frac{5}{2}}T^{-1}\mu^{\frac{1}{2}}]$ .

**Magnetic Induction** is the magnetic flux per unit of area taken perpendicular to the direction of the magnetic flux. The dimensional formula is  $[M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}\mu^{\frac{1}{2}}/L^2]$  or  $[M^{\frac{1}{2}}L^{-\frac{1}{2}}T^{-1}\mu^{\frac{1}{2}}]$ .

**Magnetic Susceptibility** is the ratio of intensity of magnetization produced and the intensity of the magnetic field producing it. The dimensional formula is  $[M^{\frac{1}{2}}L^{-\frac{1}{2}}T^{-1}\mu^{\frac{1}{2}}/M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}\mu^{-\frac{1}{2}}]$  or  $[\mu]$ .

**Current,  $I$** , flowing in circle, radius  $r$ , creates magnetic field at its center,  $2\pi I/r$ . Dimensional formula is product of formulae for magnetic field intensity and length or  $[M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}\mu^{-\frac{1}{2}}]$ .

**Quantity of Electricity** is the product of the current and time. The dimensional formula is  $[M^{\frac{1}{2}}L^{\frac{3}{2}}\mu^{-\frac{1}{2}}]$ .

**Electric Potential**, or **Electromotive Force**, as in the electrostatic system, is the ratio of work to quantity of electricity. The dimensional formula is  $[MLT^{-2}/M^{\frac{1}{2}}L^{\frac{3}{2}}\mu^{-\frac{1}{2}}]$  or  $[M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-2}\mu^{\frac{1}{2}}]$ .

**Electrostatic Capacity** is the ratio of quantity of electricity to difference of potential. The dimensional formula is  $[L^{-1}T^2\mu^{-1}]$ .

**Resistance of a Conductor** is the ratio of the difference of potential between its ends and the constant current flowing. The dimensional formula is  $[M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-2}\mu^{\frac{1}{2}}/M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}\mu^{-\frac{1}{2}}]$  or  $[LT^{-1}\mu]$ .

**Conductance** is the reciprocal of resistance, and the dimensional formula is  $[L^{-1}T\mu^{-1}]$ .

**Conductivity** is the quantity of electricity transmitted per unit area per unit potential gradient per unit of time. The dimensional formula is  $[M^{\frac{1}{2}}L\mu^{-\frac{1}{2}}/L^2(M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-2}\mu^{\frac{1}{2}}/L)T]$  or  $[L^{-2}T\mu^{-1}]$ .



**Resistivity** is the reciprocal of conductivity as just defined. The dimensional formula is  $[L^2T^{-1}\mu]$ .

**Self-inductance** is for any circuit the electromotive force produced in it by unit rate of variation of the current through it. The dimensional formula is the product of the formulae for electromotive force and time divided by that for current or  $[M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-2}\mu^{\frac{1}{2}} \times T \div M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}\mu^{-\frac{1}{2}}]$  or  $[L\mu]$ .

**Mutual Inductance** of two circuits is the electromotive force produced in one per unit rate of variation of the current in the other. The dimensional formula is the same as for self-inductance.

**Electric Field Intensity** is the ratio of electric potential or electromotive force and length. The dimensional formula is  $[M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-2}\mu^{\frac{1}{2}}]$ .

**Magnetic Reluctance** is the ratio of magnetic potential difference to magnetic flux. The dimensional formula is  $[L^{-1}\mu^{-1}]$ .

**Thermoelectric Power** is measured by the ratio of electromotive force and temperature. The dimensional formula is  $[M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-2}\mu^{\frac{1}{2}}\Theta^{-1}]$ .

**Coefficient of Peltier Effect** is measured by the ratio of the quantity of heat and quantity of electricity. The dimensional formula is  $[ML^2T^{-2}/M^{\frac{1}{2}}L^{\frac{1}{2}}\mu^{-\frac{1}{2}}]$  or  $[M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-2}\mu^{\frac{1}{2}}]$ , the same as for electromotive force.

Exs. — Find the factor required to convert intensity of magnetic field from ft.-grain-min. units to c.g.s. units. The formula is  $[m^{\frac{1}{2}}l^{-\frac{1}{2}}t^{-1}\mu^{-\frac{1}{2}}]$ ;  $m = 0.0648$ ,  $l = 30.48$ ,  $t = 60$ , and  $\mu = 1$ ; the factor is  $0.0648^{\frac{1}{2}} \times 30.48^{-\frac{1}{2}}$ , or  $0.046108$ .

How many c.g.s. units of magnetic moment make one ft.-grain-sec. unit of the same quantity? The formula is  $[m^{\frac{1}{2}}lt^{-1}\mu^{\frac{1}{2}}]$ ;  $m = 0.0648$ ,  $l = 30.48$ ,  $t = 1$ , and  $\mu = 1$ ; the number is  $0.0648^{\frac{1}{2}} \times 30.48^{\frac{1}{2}}$ , or  $1305.6$ .

If the intensity of magnetization of a steel bar is 700 in c.g.s. units, what will it be in mm.-mg.-sec. units? The formula is  $[m^{\frac{1}{2}}lt^{-1}\mu^{\frac{1}{2}}]$ ;  $m = 1000$ ,  $l = 10$ ,  $t = 1$ ,  $\mu = 1$ ; the intensity is  $700 \times 1000^{\frac{1}{2}} \times 10^{\frac{1}{2}}$ , or 70000.

Find the factor required to convert current from c.g.s. units to earth-quadrant- $10^{-11}$  gram-sec. units. The formula is  $[m^{\frac{1}{2}}lt^{-1}\mu^{-\frac{1}{2}}]$ ;  $m = 10^{11}$ ,  $l = 10^{-9}$ ,  $\mu = 1$ ; the factor is  $10^{\frac{1}{2}} \times 10^{-\frac{1}{2}}$ , or 10.

Find the factor required to convert resistance expressed in c.g.s. units into the same expressed in earth-quadrant- $10^{-11}$  gram-sec. units. The formula is  $[lt^{-1}\mu]$ ;  $l = 10^{-9}$ ,  $t = 1$ ,  $\mu = 1$ ; the factor is  $10^{-9}$ .

## FUNDAMENTAL STANDARDS.

The choice of the nature of the fundamental quantities already made does not sufficiently define the system for measurements. Some definite unit or arbitrarily chosen standard must next be taken for each of the fundamental quantities. This fundamental standard should have the qualities of permanence, reproducibility and availability and be suitable for accurate measures. Once chosen and made it is called the primary standard and is generally kept at some central bureau, — for instance, the International Bureau of Weights and Measures at Sèvres, France. A primary standard may also be chosen and made for derived units (e.g., the international ohm standard), when it is simply a standard closely representing the unit and accepted for practical purposes, its value having been fixed by certain measuring processes. Secondary or refer-

ence standards are accurately compared copies, not necessarily duplicates, of the primaries for use in the work of standardizing laboratories and the production of working standards for everyday use.

**Standard of Length.** — The primary standard of length which now almost universally serves as the basis for physical measurements is the meter. It is defined as the distance between two lines at  $0^{\circ}\text{C}$  on a platinum-iridium bar deposited at the International Bureau of Weights and Measures. This bar is known as the International Prototype Meter, and its length was derived from the "mètre des Archives," which was made by Borda. Borda, Delambre, Laplace, and others, acting as a committee of the French Academy, recommended that the standard unit of length should be the ten-millionth part of the length, from the equator to the pole, of the meridian passing through Paris. In 1795 the French Republic passed a decree making this the legal standard of length, and an arc of the meridian extending from Dunkirk to Barcelona was measured by Delambre and Mechain for the purpose of realizing the standard. From the results of that measurement the meter bar was made by Borda. The meter is now defined as above and not in terms of the meridian length; hence subsequent measures of the length of the meridian have not affected the length of the meter.

**Standard of Mass.** — The primary standard of mass now almost universally used as the basis for physical measurements is the kilogram. It is defined as the mass of a certain piece of platinum-iridium deposited at the International Bureau of Weights and Measures. This standard is known as the International Prototype Kilogram. Its mass is equal to that of the older standard, the "kilogram des Archives," made by Borda and intended to have the same mass as a cubic decimeter of distilled water at the temperature of  $4^{\circ}\text{C}$ .

Copies of the International Prototype Meter and Kilogram are possessed by the various governments and are called National Prototypes.

**Standard of Time.** — The unit of time universally used is the second. It is the mean solar second, or the 86400th part of the mean solar day. It is founded on the average time required for the earth to make one rotation on its axis relatively to the sun as a fixed point of reference.

**Standard of Temperature.** — The standard scale of temperature as adopted by the International Committee of Weights and Measures (1887) depends on the constant-volume hydrogen thermometer. The hydrogen is taken at an initial pressure at  $0^{\circ}\text{C}$  of one meter of mercury,  $0^{\circ}\text{C}$ , sea-level at latitude  $45^{\circ}$ . The scale is defined by designating the temperature of melting ice as  $0^{\circ}$  and of condensing steam as  $100^{\circ}$  under standard atmospheric pressure. This is known as the Centigrade scale (abbreviated C).

A scale independent of the properties of any particular substance, and called the thermodynamic, or absolute scale, was proposed in 1848 by Lord Kelvin. In it the temperature is proportional to the average kinetic energy per molecule of a perfect gas. The temperature of melting ice is taken as  $273.15^{\circ}$ , that of the boiling point,  $373.15^{\circ}$ . The scale of the hydrogen thermometer varies from it only in the sense that the behavior of hydrogen departs from that of a perfect gas. It is customary to refer to this scale as the Kelvin scale (abbreviated K).

## NUMERICALLY DIFFERENT SYSTEMS OF UNITS.

The fundamental physical quantities which form the basis of a system for measurements have been chosen and the fundamental standards selected and made. Custom has not however generally used these standards for the measurement of the magnitudes of quantities but rather multiples or submultiples of them. For instance, for very small quantities the micron ( $\mu$ ) or one-millionth of a meter is often used. The following table<sup>1</sup> gives some of the systems proposed, all built upon the fundamental standards already described. The centimeter-gram-second (cm-g-sec. or c.g.s.) system proposed by Kelvin is the only one generally accepted.

TABLE I.  
PROPOSED SYSTEMS OF UNITS.

	Weber and Gauss	Kelvin c.g.s.	Moon 1891	Giorgi MKS (Prim. Stds.)	France 1914	B. A. Com., 1863	Practical (B. A. Com., 1873)	Strout 1891
Length	mm	cm	dm	m	m	m	$10^9$ cm	$10^9$ cm
Mass	mg	g	Kg	Kg	$10^6$ g	g	$10^{-11}$ g	$10^{-9}$ g
Time	sec.	sec.	$\frac{\text{sec.}}{10}$	sec.	sec.	sec.	sec.	sec.

Further the choice of a set of fundamental physical quantities to form the basis of a system does not necessarily determine how that system shall be used in measurements. In fact, upon any sufficient set of fundamental quantities, a great many different systems of units may be built. The electrostatic and electromagnetic systems are really systems of electric quantities rather than units. They were based upon the relationships  $F = QQ'/Kr^2$  and  $mm'/\mu r^2$ , respectively. Systems of units built upon a chosen set of fundamental physical quantities may differ in two ways: (1) the units chosen for the fundamental quantities may be different; (2) the defining equations by which the system is built may be different.

The electrostatic system generally used is based on the centimeter, gram, second, and dielectric constant of a vacuum. Other systems have appeared, differing from this in the first way, — for instance using the foot, grain and second in place of the centimeter, gram and second. A system differing from it in the second way is that of Heaviside which introduces the factor  $4\pi$  at different places than is usual in the equations. There are similarly several systems of electromagnetic units in use.

**Gaussian Systems.** — “The complexity of the interrelations of the units is increased by the fact that not one of the systems is used as a whole, consistently for all electromagnetic quantities. The ‘systems’ at present used are therefore combinations of certain of the systems of units.

<sup>1</sup> Circular 60 of the Bureau of Standards, Electric Units and Standards, 1916. The subsequent matter in this introduction is based upon this circular.

"Some writers <sup>1</sup> on the theory of electricity prefer to use what is called a Gaussian system, a combination of electrostatic units for purely electrical quantities and electromagnetic units for magnetic quantities. There are two such Gaussian systems in vogue, -- one a combination of c.g.s. electrostatic and c.g.s. electromagnetic systems, and the other a combination of the two corresponding Heaviside systems.

"When a Gaussian system is used, caution is necessary when an equation contains both electric and magnetic quantities. A factor expressing the ratio between the electrostatic and electromagnetic units of one of the quantities has to be introduced. This factor is the first or second power of  $c$ , the number of electrostatic units of electric charge in one electromagnetic unit of the same. There is sometimes a question as to whether electric current is to be expressed in electrostatic or electromagnetic units, since it has both electric and magnetic attributes. It is usually expressed in electrostatic units in the Gaussian system."

It may be observed from the dimensions of  $K$  given in Table 1 that  $[1/K\mu] = [L^2/T^2]$  which has the dimensions of a square of a velocity. This velocity was found experimentally to be equal to that of light, when  $K$  and  $\mu$  were expressed in the same system of units. Maxwell proved theoretically that  $1/\sqrt{K\mu}$  is the velocity of any electromagnetic wave. This was subsequently proved experimentally. When a Gaussian system is used, this equation becomes  $c = 1/\sqrt{K\mu} = v$ . For the ether  $K = 1$  in electrostatic units and  $\mu = 1$  in electromagnetic units. Hence  $c = v$  for the ether, or the velocity of an electromagnetic wave in the ether is equal to the ratio of the c.g.s. electromagnetic to the c.g.s. electrostatic unit of electric charge. This constant  $c$  is of primary importance in electrical theory. Its most probable value is  $2.9986 \times 10^{10}$  centimeters per second.

**"Practical" Electromagnetic System.** This electromagnetic system is based upon the units of  $10^9$  cm,  $10^{-11}$  gram, the sec. and  $\mu$  of the ether. It is never used as a complete system of units but is of interest as the historical basis of the present International System. The principal quantities are the resistance unit, the ohm =  $10^9$  c.g.s. units; the current unit, the ampere =  $10^{-1}$  c.g.s. units; and the electromotive force unit, the volt =  $10^8$  c.g.s. units.

**The International Electric Units.** -- The units used in practical measurements, however, are the "International Units." They were derived from the "practical" system just described, or as the latter is sometimes called, the "absolute" system. These international units are based upon certain concrete standards presently to be defined and described. With such standards electrical comparisons can be more accurately and readily made than could absolute measurements in terms of the fundamental units. Two electric units, the international ohm and the international ampere, were chosen and made as nearly equal as possible to the ohm and ampere of the "practical" or "absolute" system.

<sup>1</sup> For example, A. G. Webster, "Theory of Electricity and Magnetism," 1897; J. H. Jeans, "Electricity and magnetism," 1911; H. A. Lorentz, "The Theory of Electrons," 1909; and O. W. Richardson, "The Electron Theory of Matter," 1914.

This system of units, sufficiently near to the "absolute" system for the purpose of electrical measurements and as a basis for legislation, was defined as follows:

"1. The *International Ohm* is the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grams in mass, of a constant cross-sectional area and of a length of 106,300 centimeters.

"2. The *International Ampere* is the unvarying electric current which, when passed through a solution of nitrate of silver in water, in accordance with specification II attached to these Resolutions, deposits silver at the rate of 0.00111800 of a gram per second.

"3. The *International Volt* is the electrical pressure which, when steadily applied to a conductor the resistance of which is one international ohm will produce a current of one international ampere.

"4. The *International Watt* is the energy expended per second by an unvarying electric current of one international ampere under the pressure of one international volt."

In accordance with these definitions, a value was established for the electromotive force of the recognized standard of electromotive force, the Weston normal cell, as the result of international coöperative experiments in 1910. The value was 1.0183 international volts at 20° C.

The definitions by the 1908 International Conference supersede certain definitions adopted by the International Electrical Congress at Chicago in 1893. Certain of the units retain their Chicago definitions, however. They are as follows:

"*Coulomb*. As a unit of quantity, the *International Coulomb*, which is the quantity of electricity transferred by a current of one international ampere in one second.

"*Farad*. As a unit of capacity, the *International Farad*, which is the capacity of a condenser, charged to be a potential of one international volt by one international coulomb of electricity.

"*Joule*. As a unit of work, the *Joule*, which is equal to  $10^7$  units of work in the c.g.s. system, and which is represented sufficiently well for practical use by the energy expended in one second by an international ampere in an international ohm.

"*Henry*. As the unit of induction, the *Henry*, which is the induction in a circuit when the electromotive force induced in this circuit is one international volt, while the inducing current varies at the rate of one ampere per second."

"The choice of the ohm and ampere as fundamental was purely arbitrary. These are the two quantities directly measured in absolute electrical measurements. The ohm and volt have been urged as more suitable for definition in terms of arbitrary standards, because the primary standard of electromotive force (standard cell) has greater simplicity than the primary standard of current (silver voltameter). The standard cell is in fact used, together with resistance standards, for the actual maintenance of the units, rather than the silver voltameter and resistance standards. Again, the volt and ampere have some claim

for consideration for fundamental definition, both being units of quantities more fundamental in electrical theory than resistance."

For all practical purposes the "international" and the "practical" or "absolute" units are the same. Experimental determination of the ratios of the corresponding units in the two systems have been made and the mean results are given in Table 382. These ratios represent the accuracy with which it was possible to fix the values of the international ohm and ampere at the time they were defined (London Conference of 1908). It is unlikely that the definitions of the international units will be changed in the near future to make the agreement any closer. An act approved July 12, 1894, makes the International units as above defined the legal units in the United States of America.

## THE STANDARDS OF THE INTERNATIONAL ELECTRICAL UNITS.

### RESISTANCE

**Resistance.** — The definition of the international ohm adopted by the London Conference in 1908 is accepted practically everywhere.

**Mercury Standards.** — Mercury standards conforming to the definition were constructed in England, France, Germany, Japan, Russia and the United States. Their mean resistances agree to about two parts in 100,000. To attain this accuracy, elaborate and painstaking experiments were necessary. Tubes are never quite uniform in cross-section; the accurate measurement of the mass of mercury filling the tube is difficult, partly because of a surface film on the walls of the tube; the greatest refinements are necessary in determining the length of the tube. In the electrical comparison of the resistance with wire standards, the largest source of error is in the filling of the tube. These and other sources of error necessitated a certain uniformity in the setting up of mercury standards and at the London Conference the following specifications were drawn up:

### SPECIFICATION RELATING TO MERCURY STANDARDS OF RESISTANCE.

The glass tubes used for mercury standards of resistance must be made of a glass such that the dimensions may remain as constant as possible. The tubes must be well annealed and straight. The bore must be as nearly as possible uniform and circular, and the area of cross section of the bore must be approximately one square millimeter. The mercury must have a resistance of approximately one ohm.

Each of the tubes must be accurately calibrated. The correction to be applied to allow for the area of the cross-section of the bore not being exactly the same at all parts of the tube must not exceed 5 parts in 10,000.

The mercury filling the tube must be considered as bounded by plane surfaces placed in contact with the ends of the tube.

The length of the axis of the tube, the mass of mercury the tube contains, and the electrical resistance of the mercury are to be determined at a temperature as near to  $0^{\circ}\text{C}$  as possible. The measurements are to be corrected to  $0^{\circ}\text{C}$ .

For the purpose of the electrical measurements, end vessels carrying connections for the current and potential terminals are to be fitted on to the tube. These end vessels are to be spherical in shape (of a diameter of approximately four centimeters) and should have cylindrical pieces attached to make connections with the tubes. The outside edge of each end of the tube

is to be coincident with the inner surface of the corresponding end vessel. The leads which make contact with the mercury are to be of thin platinum wire fused into glass. The point of entry of the current lead and the end of the tube are to be at opposite ends of a diameter of the bulb; the potential lead is to be midway between these two points. All the leads must be so thin that no error in the resistance is introduced through conduction of heat to the mercury. The filling of the tube with mercury for the purpose of the resistance measurements must be carried out under the same conditions as the filling for the determination of the mass.

The resistance which has to be added to the resistance of the tube to allow for the effect of the end vessels is to be calculated by the formula

$$A = \frac{0.80}{1063\pi} \left( \frac{1}{r_1} + \frac{1}{r_2} \right) \text{ ohm,}$$

where  $r_1$  and  $r_2$  are the radii in millimeters of the end sections of the bore of the tube.

The mean of the calculated resistances of at least five tubes shall be taken to determine the value of the unit of resistance.

For the purpose of the comparison of resistances with a mercury tube the measurements shall be made with at least three separate fillings of the tube.

**Secondary Standards.** — Secondary standards, derived from the mercury standards and used to give values to working standards, are certain coils of manganin wire kept in the national laboratories. Their resistances are adjusted to correspond to the unit or its decimal multiples or submultiples. The values assigned to these coils are checked from time to time with the similar coils of the other countries. The value now in use is based on the comparison made at the U. S. Bureau of Standards in 1910 and may be called the "1910 ohm." Later measurements on various mercury standards checked the value then used within 2 parts in 100,000. Thus the basis of resistance measurement is maintained not by the mercury standards of a single laboratory, but by all the mercury standards of the various national laboratories; it is furthermore the same in all countries, except for very slight outstanding discrepancies due to the errors of measurement and variations of the standards with time.

**Resistance Standards in Practice.** — In ordinary measurements, working standards of resistance are usually coils of manganin wire (approximately 84 per cent Cu + 12 per cent Mn + 4 per cent Ni). They are generally used in oil which carries away the heat developed by the current and facilitates regulation and measurement of the temperature. The best type is inclosed in a sealed case for protection against atmospheric humidity. Varying humidity changes the resistance of open coils often to several parts in 10,000 higher in summer than in winter. While sealed 1 ohm and 0.1 ohm coils may remain constant to about 1 part in 100,000.

**Absolute Ohm.** — The absolute measurement of resistance involves the precise determination of a length and a time (usually an angular velocity) in a medium of unit permeability. Since the dimensional formula of resistance in the electromagnetic system is  $[L\mu/T]$ , such an absolute measurement gives  $R$  not in cm/sec. but in  $\text{cm} \times \mu/\text{sec}$ . The definitions of the ohm, ampere and volt by the 1908 London conference tacitly assume a permeability equal to unity. The relation of the international ohm to the absolute ohm has been measured in different ways involving revolving coil, revolving disk, and alternate current methods. Probably the most accurate determination was made

in 1913 by F. E. Smith of the National Physical Laboratory of England, using a modification of the Lorentz revolving disk method. His result was

$$1 \text{ international ohm} = 1.00052 \pm 0.00004 \text{ absolute ohms,}$$

or, in other words, while one international ohm is represented by a mercury column 106.300 cm long as specified above, one absolute ohm requires a similar column 106.245 cm long. Table 305 of the 6th revised edition of these tables contains data relative to the various determinations of the ohm.

#### CURRENT.

**The Silver Voltameter.** — The silver voltameter is a concrete means of measuring current in accordance with the definition of the international ampere. As used for the realization of the international ampere "it consists of a platinum cathode in the form of a cup holding the silver nitrate solution, a silver anode partly or wholly immersed in the solution, and some means to prevent anode slime and particles of silver mechanically detached from the anode from reaching the cathode. As a standard representing the international ampere, the silver voltameter includes also the chronometer used to measure time. The degree of purity and the mode of preparation of the various parts of the voltameter affect the mass of the deposit. There are numerous sources of error, and the suitability of the silver voltameter as a primary standard of current has been under investigation since 1893. Differences of as much as 0.1 per cent or more may be obtained by different procedures, the larger differences being mainly due to impurities produced in the electrolyte (by filter paper, for instance). Hence, in order that the definition of current be precise, it must be accompanied by *specifications* for using the voltameter."

The original specifications were recognized to be inadequate and an international committee on electrical units and standards was appointed to complete the specifications. It was also recognized that in practice standard cells would replace secondary current standards so that a value must be fixed for the electromotive force of the Weston normal cell. This was attempted in 1910 at the Bureau of Standards by representatives of that institution together with one delegate each from the Physikalische-Technische Reichsanstalt, The National Physical Laboratory and the Laboratoire Central d'Electricité. Voltameters from all four institutions were put in series under a variety of experimental conditions. Standard Weston cells and resistance standards of the four laboratories were also intercompared. From the joint comparison of standard cells and silver voltameters particular values were assigned to the standard cells from each laboratory. The different countries thus have a common basis of measurement maintained by the aid of standard cells and resistance standards derived from the international voltameter investigation of 1910.

It was not found possible to draw up satisfactory and final specifications for the silver voltameter. Provisional specifications were submitted by the U. S. Bureau of Standards and more complete specifications have been proposed in correspondence between the national laboratories and members of the inter-



national committee since 1910, but no agreement upon final specifications has yet been reached.

**Resistance Standards Used in Current Measurements.** — Precise measurements of currents require a potentiometer, a standard cell and a resistance standard. The resistance must be so designed as to carry the maximum current without undue heating and consequent change of resistance. Accordingly the resistance metal must have a small temperature resistance coefficient and a sufficient area in contact with the air, oil, or other cooling fluid. It must have a small thermal electromotive force against copper. Manganin satisfies these conditions and is usually used. The terminals of the standard must have sufficient contact area so that there shall be no undue heating at contacts.<sup>1</sup> It must be so designed that the current distribution does not depend upon the mode of connection to the circuit.

**Absolute Ampere.** The absolute ampere ( $10^{-1}$ c.g.s. electromagnetic units) differs by a negligible amount from the international ampere. Since the dimensional formula of the current in the electromagnetic system is  $[L^{\frac{1}{2}}M^{\frac{1}{2}}/T\mu^{\frac{1}{2}}]$  which is equivalent to  $[F^{\frac{1}{2}}/\mu^{\frac{1}{2}}]$ , the absolute measurement of current involves fundamentally the measurement of a force in a medium of unit permeability. In most measurements of high precision an electro-dynamometer has been used of the form known as a current balance. A summary of the various determinations will be found in Table 203 of the 6th Revised Edition of these tables.

The best value is probably the mean of the determinations made at the U. S. Bureau of Standards, the National Physical Laboratory and at the University of Gröningen, which gives

$$1 \text{ international ampere} = 0.99991 \text{ absolute ampere.}$$

The separate values were 0.99992, 0.99988 and 0.99994, respectively. "The result may also be expressed in terms of the electrochemical equivalent of silver, which, based on the '1910 mean voltameter,' thus equals 0.00111810 g per absolute coulomb. By the definition of the international ampere, the value is 0.00111800 g per international coulomb."

#### ELECTROMOTIVE FORCE.

**International Volt.** — "The international volt is derived from the international ohm and ampere by Ohm's law. Its value is maintained by the aid of the Weston normal cell. The national standardizing laboratories have groups of such cells, to which values in terms of the international ohm and ampere have been assigned by international experiments, and thus form a basis of reference for the standardization of the standard cells used in practical measurements."

**Weston Normal Cell.** — The Weston normal cell is the standard used to maintain the international volt and, in conjunction with resistance standards, to maintain the international ampere. The cell is a simple voltaic combination

<sup>1</sup> See "Report to the International Committee on Electrical Units and Standards," 1912, p. 199. For the Bureau of Standards investigations see Bull. Bureau of Standards, 9, pp. 209, 493; 10, p. 475, 1912-14; 13, p. 147, 1915; 9, p. 151, 1912; 13, pp. 447, 479, 1916.

having its anode or negative electrode of cadmium amalgam, consisting of 10 per cent by weight of cadmium and 90 per cent mercury. The cathode, or positive electrode, is pure mercury covered with a paste consisting of mercurous sulphate, cadmium-sulphate crystals, and solution. The electrolyte is cadmium-sulphate solution in contact with an excess of cadmium-sulphate crystals. The containing vessel is of glass, usually in the H form. Connection is made to the electrodes by platinum wires sealed into the glass. The cells are sealed, preferably hermetically, and in use are submerged in a constant-temperature oil bath. The resistance of a cell is about 600 to 1000 ohms. The Weston cell used with potentiometers is not the Weston normal cell, but differs from it only slightly, the cadmium-sulphate solution not being saturated. It is described in the next section below.

One of the great advantages of the Weston normal cell is its small change of electromotive force with change of temperature. At any temperature,  $t$  (centigrade), between  $0^\circ$  and  $40^\circ$ ,  $E_t = E_{20} - 0.0000406 (t - 20) - 0.0000095 (t - 20)^2 + 0.0000001 (t - 20)^3$ . This temperature formula was adopted by the London conference of 1908. That this formula may apply, the cell must be of a strictly uniform temperature throughout. One leg of the cell has a large positive and the other leg a large negative temperature coefficient. If the temperature of one leg changes faster than the other, the formula does not hold.

When the best of care is taken as to purity of materials and mode of procedure, Weston normal cells are reproducible within 1 part in 100,000. The source of the greatest variations has probably been in the mercurous sulphate. Cells using the best samples of this material have an electromotive force the constancy of which over a period of one year is about 1 part in 100,000. Only very meager specifications for the cell have as yet been agreed upon internationally, however, and the procedures in various laboratories differ in some respects.<sup>1</sup>

The basis of measurements of electromotive force is the same in all countries as the result of the joint international experiments of 1910. As already stated, a large number of observations were made at that time with the silver voltameter, and a considerable number of Weston normal cells from the national laboratories of England, France, Germany and the United States were compared. From the results of these voltameter experiments and from resistance measurements, the value

$$1.0183 \text{ international volts at } 20^\circ \text{ C}$$

was assigned to the Weston normal cell. A mean of the groups of cells from the four laboratories was taken as most accurately representing the Weston normal

<sup>1</sup> For the preliminary specifications which have been issued and the reports of the various investigations on the standard cells see the following references: Preliminary specifications, Wolff and Waters, Bull. B. of S. 3, p. 623, 1907; Clark and Weston Standard Cells, Wolff and Waters, ditto, 4, p. 1, 1907; Temperature formula of Weston Standard Cell, ditto, 5, p. 309, 1908; The materials, reproducibility, etc., of the Weston Cell, Helett, Phys. Rev. 22, p. 321, 1906; 23, p. 166, 1906; 27, pp. 33, 337, 1908; Mercurous sulphate, etc., Steinwehr, Zs. für Electroch. 12, p. 578, 1906; German value of cell, Jaeger and Steinwehr, ditto, 28, p. 367, 1908; National Physical Laboratory researches, Smith, Phil. Trans. 207, p. 393, 1908; On the Weston Cell, Haga and Boerema, Arch. Neerland, des Sci. Exactes, 3, p. 324, 1913.

cell. Each laboratory has means of preserving the unit. Any discrepancies between the bases of the different countries at the present time would be due only to possible variations in the reference cells of the national laboratories. Such discrepancies are probably less than 2 parts in 100,000.

The figure 1.0183 has been in use since January 1, 1911. The value used in the United States before 1911, 1.019126 at 20° C or 1.0189 at 25° C, was assigned to a certain group of cells maintained as the standard of electromotive force at the Bureau of Standards. The high value is partly due to the use of commercial mercurous sulphate in the cells. The old and the new values, 1.01926 and 1.0183, thus apply to different groups of cells. The group of cells to which the value 1.019126 was assigned before 1910 differed by 26 microvolts from the mean of the international group, such that the international group to which the value 1.0183 is now assigned had the value  $1.019126 + 0.000026$ , or 1.019152, in terms of the old United States basis. The difference between 1.019152 and 1.0183 is 0.000852.

The electromotive force of any Weston cell as now given is therefore 0.000852 volt smaller than on the old United States basis, i.e., the present international volt is 84 parts in 100,000 larger than the old international volt of the United States.

Upon the new international basis the Clark cell set up according to the old United States legal specifications has an emf of 1.4328<sub>0</sub> international volts at 15° C. The Clark cell set up (with specially purified mercurous sulphate) according to improved specifications used at the Bureau of Standards has an emf of 1.4325<sub>0</sub> international volts at 15° C or 1.4263<sub>7</sub> at 20° C.

**Portable Weston Cells.** — The standard cell used in practice is the Weston portable cell. It is like the Weston normal cell except that the cadmium-sulphate solution at ordinary temperatures is unsaturated. As usually made, the cadmium-sulphate solution is saturated at about 4° C; at higher temperatures the crystals are dissolved. Plugs of asbestos or other material hold the chemicals in place. Its resistance is usually about 200 to 311 ohms. The change of emf, wholly negligible in most electrical measurements, is less than 0.00001 volt per degree C. The two legs of the cell have large and opposite temperature coefficients so that care must be taken that the temperature of the cell is kept uniform and the cell must be protected from draughts or large changes of temperature. The electromotive force of a portable cell ranges from 1.0181 to 1.0191 international volts and must be determined by comparison with standards. It decreases very slightly with time, usually less than 0.0001 volt per year.

**Absolute and Semi-absolute Volt.** — Since the direct determination of the volt in absolute measure presents great difficulties, it is derived by Ohm's law from the absolute measures of the ohm and ampere. From the absolute values of these already given,

$$1 \text{ international volt} = 1.00043 \text{ absolute volts.}$$

The electromotive force of the Weston normal cell at 20° C is 1.0183<sub>0</sub> international volts and 1.0187<sub>4</sub> absolute volts. A semi-absolute volt is that potential.

difference which exists between the terminals of a resistance of one *international* ohm when the latter carries a current of one *absolute* ampere. The emf of the Weston normal cell may be taken as 1.01821 semi-absolute volts at 20° C.

#### QUANTITY OF ELECTRICITY.

The international unit of quantity of electricity is the coulomb. The faraday is the quantity of electricity necessary to liberate 1 gram equivalent in electrolysis. It is equivalent to 96,500 coulombs.

**Standards.** — There are no standards of electric quantity. The silver voltameter may be used for its measurement since under ideal conditions the mass of metal deposited is proportional to the amount of electricity which has flowed.

#### CAPACITY.

The unit generally used for capacity is the international microfarad or the one-millionth of the international farad. Capacities are commonly measured by comparison with standard capacities. The values of the standards are determined by measurement in terms of resistance and time. The standard is some form of condenser consisting of two sets of metal plates separated by a dielectric. The condenser should be surrounded by a metal shield connected to one set of plates rendering the capacity independent of the surroundings. An ideal condenser would have a constant capacity under all circumstances, with zero resistance in its leads and plates, and no absorption in the dielectric. Actual condensers vary with the temperature, atmospheric pressure, and the voltage, frequency, and time of charge and discharge. A well-constructed air condenser with heavy metal plates and suitable insulating supports is practically free from these effects and is used as a standard of capacity.

Practically air condenser plates must be separated by 1 mm or more and so cannot be of great capacity. The more the capacity is increased by approaching the plates, the less the mechanical stability and the less constant the capacity. Condensers of great capacity use solid dielectrics, preferably mica sheets with conducting plates of tinfoil. At constant temperature the best mica condensers are excellent standards. The dielectric absorption is small but not quite zero, so that the capacity of these standards with different methods of measurement must be carefully determined.

#### INDUCTANCE.

The henry, the unit of self-inductance, is also the unit of mutual inductance. The henry has been known as the "quadrant" and the "secohm." The length of a quadrant or quarter of the earth's circumference is approximately  $10^9$  cms. and a henry is  $10^9$  cms. of inductance. Secohm is a contraction of second and ohm; the dimensions of inductance are  $[TR]$  and this unit is based on the second and ohm.

**Inductance Standards.** — Inductance standards are measured in international units in terms of resistance and time or resistance and capacity by alternate-

current bridge methods. Inductances calculated from dimensions are in absolute electromagnetic units. The ratio of the international to the absolute henry is the same as the ratio of the corresponding ohms.

Since inductance is measured in terms of capacity and resistance by the bridge method about as simply and as conveniently as by comparison with standard inductances, it is not necessary to maintain standard inductances. They are however of value in magnetic, alternating-current, and absolute electrical measurements. A standard inductance is a circuit so wound that when used in a circuit it adds a definite amount of inductance. It must have either such a form or so great an inductance that the mutual inductance of the rest of the circuit upon it may be negligible. It usually is a wire coil wound all in the same direction to make self-induction a maximum. A standard, the inductance of which may be calculated from its dimensions, should be a single layer coil of very simple geometrical form. Standards of very small inductance, calculable from their dimensions, are of some simple device, such as a pair of parallel wires or a single turn of wire. With such standards great care must be used that the mutual inductance upon them of the leads and other parts of the circuit is negligible. Any inductance standard should be separated by long leads from the measuring bridge or other apparatus. It must be wound so that the distributed capacity between its turns is negligible; otherwise the apparent inductance will vary with the frequency.

#### POWER AND ENERGY.

Power and energy, although mechanical and not primarily electrical quantities, are measurable with greater precision by electrical methods than in any other way. The watt and the electric units were so chosen in terms of the c.g.s. units that the product of the current in amperes by the electromotive force in volts gives the power in watts (for continuous or instantaneous values). The international watt, defined as "the energy expended per second by an unvarying electric current of one international ampere under an electric pressure of one international volt," differs but little from the absolute watt.

**Standards and Measurements.** — No standard is maintained for power or energy. Measurements are always made in electrical practice in terms of some of the purely electrical quantities represented by standards.

#### MAGNETIC UNITS.

C.G.S. units are generally used for magnetic quantities. American practice is fairly uniform in names for these units: the c.g.s. unit of magnetomotive force is called the "gilbert," of reluctance, the "oersted," following the provisional definitions of the American Institute of Electrical Engineers (1894). The c.g.s. unit of flux is called the "maxwell" as defined by the 1900 Paris conference. The name "gauss" is used unfortunately both for the unit of induction (A.I.E.E. 1894) and for the unit of magnetic field intensity or magnetizing force. "This double usage, recently sanctioned by engineering societies, is based upon the mathematical convenience of defining both induction and magnetizing force

as the force on a unit magnetic pole in a narrow cavity in the material, the cavity being in one case perpendicular, in the other parallel, to the direction of the magnetization: this definition however applies only in the ordinary electro-magnetic units. There are a number of reasons for considering induction and magnetizing force as two physically distinct quantities, just as electromotive force and current are physically different."

In the United States "gauss" has been used much more for the c.g.s. unit of induction than for the unit of magnetizing force. The longer name of "maxwell per cm<sup>2</sup>" is also sometimes used for this unit when it is desired to distinguish clearly between the two quantities. The c.g.s. unit of magnetizing force is usually called the "gilbert per cm."

A unit frequently used is the ampere-turn. It is a convenient unit since it eliminates  $4\pi$  in certain calculations. It is derived from the "ampere turn per cm." The following table shows the relations between a system built on the ampere-turn and the ordinary magnetic units.<sup>1</sup>

TABLE II.  
THE ORDINARY AND THE AMPERE-TURN MAGNETIC UNITS.

Quantity		Ordinary magnetic units.	Ampere-turn units.	Ordinary units in 1 ampere-turn unit
Magnetomotive force	$\mathcal{F}$	Gilbert	Ampere-turn	$4\pi/10$
Magnetizing force	$H$	Gilbert per cm.	Ampere-turn per cm.	$4\pi/10$
Magnetic flux	$\Phi$	Maxwell	Maxwell	1
Magnetic induction	$B$	{ Maxwell per cm. <sup>2</sup> Gauss	{ Maxwell per cm. <sup>2</sup> Gauss	1
Permeability	$\mu$	Oersted	{ Ampere-turn per Maxwell Maxwell per cm. <sup>2</sup>	1
Reluctance	$R$			$4\pi/10$
Magnetization intensity	$J$			$1/4\pi$
Magnetic susceptibility	$\kappa$			$1/4\pi$
Magnetic pole strength	$m$		Maxwell	$1/4\pi$

<sup>1</sup> Dellinger, International System of Electric and Magnetic Units, Bull. Bureau of Standards, 13, p. 599, 1916.

# PHYSICAL TABLES

## SPELLING AND ABBREVIATIONS OF THE COMMON UNITS OF WEIGHT AND MEASURE.

The spelling of the metric units is that adopted by the International Committee on Weights and Measures and given in the law legalizing the metric system in the United States (1866). The period is omitted after the metric abbreviations but not after those of the customary system. The exponents "2" and "3" are used to signify area and volume respectively in the metric units. The use of the same abbreviation for singular and plural is recommended. It is also suggested that only small letters be used for abbreviations except in the case of A. for acre, where the use of the capital letter is general. The following list is taken from circular 87 of the U. S. Bureau of Standards.

Unit.	Abbreviation	Unit.	Abbreviation
acre	A	kilogram	kg
are	a	kiloliter	kl
avoirdupois	av.	kilometer	km
barrel	bbl.	link	li.
board foot	bd. ft.	liquid	liq.
bushel	bu.	liter	l
carat, metric	c	meter	m
centare	ca	metric ton	t
centigram	cg	micron	$\mu$
centiliter	cl	mile	mi.
centimeter	cm	milligram	mg
chain	ch.	milliliter	ml
cubic centimeter	cm <sup>3</sup>	millimeter	mm
cubic decimeter	dm <sup>3</sup>	millimicron	m $\mu$
cubic dekameter	dkm <sup>3</sup>	minim	mm. or m
cubic foot	cu. ft.	ounce	oz.
cubic hectometer	hm <sup>3</sup>	ounce, apothecaries'	oz. ap. or 3
cubic inch	cu. in.	ounce, avoirdupois	oz. av.
cubic kilometer	km <sup>3</sup>	ounce, fluid	fl. oz.
cubic meter	m <sup>3</sup>	ounce, troy	oz. t.
cubic mile	cu. mi.	peck	pk.
cubic millimeter	mm <sup>3</sup>	pennyweight	dwt.
cubic yard	cu. yd.	pint	pt.
decigram	dg	pound	lb.
deciliter	dl	pound, apothecaries'	lb. ap.
decimeter	dm	pound, avoirdupois	lb. av.
decistere	ds	pound, troy	lb. t.
dekagram	dkg	quart	qt.
dekaliter	dkl	rod	rd.
dekameter	dkm	scruple, apothecaries'	s. ap. or 3
dekastere	dks	square centimeter	cm <sup>2</sup>
dram	dr.	square chain	sq. ch.
dram, apothecaries'	dr. ap. or 3	square decimeter	dm <sup>2</sup>
dram, avoirdupois	dr. av.	square dekameter	dkm <sup>2</sup>
dram, fluid	fl. dr.	square foot	sq. ft.
fathom	fath.	square hectometer	hm <sup>2</sup>
foot	ft.	square inch	sq. in.
firkin	fir.	square kilometer	km <sup>2</sup>
furlong	fur.	square meter	m <sup>2</sup>
gallon	gal.	square mile	sq. mi.
grain	gr.	square millimeter	mm <sup>2</sup>
gram	g	square rod	sq. rd.
hectare	ha	square yard	sq. yd.
hectogram	hg	stere	s
hectoliter	hl	ton	tn.
hectometer	hm	ton, metric	t
hogshead	hhd.	troy	t.
hundredweight	cwt.	yard	yd.
inch	in.		



## Conversion Factors.

To change a quantity from one system of units to another: substitute in the corresponding conversion factor from the following table the ratios of the magnitudes of the *old* units to the *new* and multiply the old quantity by the resulting number. For example: to reduce velocity in miles per hour to feet per second, the conversion factor is  $1\frac{1}{2}$ ;  $1 = 5280/1$ ,  $1 = 3600/1$ , and the factor is  $5280/3600$  or  $1.467$ . Or we may proceed as follows: e. g., to find the equivalent of 1 c.g.s. unit of angular momentum in the p.d.t.t.m. unit, from the Table 1 g. cm<sup>2</sup>/sec. = 1 lb. ft.<sup>2</sup>/min., where  $x$  is the factor sought. Solving,  $x = 1\text{g./lb.} \times \text{cm}^2/\text{ft.}^2 \times \text{min./sec.} = 1 \times .002205 \times .001076 \times 60 = .0001475$ .

The dimensional formulae lack one quality which is needed for completeness, an indication of their vector characteristics; such characteristics distinguish plane and solid angle, torque and energy, illumination and brightness.

## (a) FUNDAMENTAL UNITS.

The fundamental units and conversion factors in the systems of units most commonly used are: Length [ $l$ ]; Mass [ $m$ ]; Time [ $t$ ]; Temperature [ $\theta$ ]; and for the electrostatic system, Dielectric Constant [ $k$ ]; for the electromagnetic system, Permeability [ $\mu$ ]. The formulae will also be given for the International System of electric and magnetic units based on the units length, resistance [ $r$ ], current [ $i$ ], and time.

## (b) DERIVED UNITS.

Name of unit. (Geometrical and dynamical)	Conversion factor. [ $m^l t^p$ ]			Name of units. (Heat and light.)	Conversion factor. [ $m^l t^p \theta^v$ ]			
	x	y	z		x	y	z	v
Area, surface. . . . .	0	2	0	Quantity of heat:				
Volume. . . . .	0	3	0	thermal units. . . . .	1	0	0	1
Angle. . . . .	0	0	0	thermometric units. . . . .	0	3	0	1
				dynamical units. . . . .	1	2	-2	0
Solid angle. . . . .	0	0	0					
Curvature. . . . .	0	-1	0	Coefficient of thermal				
Angular velocity. . . . .	0	0	-1	expansion. . . . .	0	0	0	-1
Linear velocity. . . . .	0	1	-1	Thermal conductivity:				
Angular acceleration. . . . .	0	0	-2	thermal units. . . . .	1	-1	-1	0
Linear acceleration. . . . .	0	1	-2	thermometric units				
				or diffusivity. . . . .	0	2	-1	0
Density. . . . .	1	-3	0	dynamical units. . . . .	1	1	-3	-1
Moment of inertia. . . . .	1	2	0					
Intensity of attraction. . . . .	0	1	-2	Thermal capacity. . . . .	1	0	0	0
Momentum. . . . .	1	1	1	Latent heat:				
Moment of momentum. . . . .	1	2	1	thermal units. . . . .	0	0	0	1
Angular momentum. . . . .	1	2	-1	dynamical units. . . . .	0	2	-2	0
Force. . . . .	1	1	-2	Joule's equivalent. . . . .	0	2	-2	1
Moment of couple,								
torque. . . . .	1	2	-2	Entropy:				
Work, energy. . . . .	1	2	-2	heat in thermal units	1	0	0	0
				heat in dynamical				
Power, activity. . . . .	1	2	-3	units. . . . .	1	2	-2	1
Intensity of stress. . . . .	1	-1	-2					
Modulus of elasticity. . . . .	1	-1	-2	Luminous intensity. . . . .	0	0	0	1*
				Illumination. . . . .	0	-2	0	1*
Compressibility. . . . .	-1	1	2	Brightness. . . . .	0	2	0	1*
Resilience. . . . .	1	-1	-2	Visibility. . . . .	-1	2	3	1*
Viscosity. . . . .	1	-1	-1	Luminous efficiency. . . . .	-1	-2	3	1*

\* For these formulae the numbers in the last column are the exponents of  $F$  where  $F$  refers to the luminous flux. For definitions of these quantities see Table 299, page 299.